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Farmers' Participatory Alternate Wetting and Drying Irrigation Method Reduces Greenhouse Gas Emission and Improves Water Productivity and Paddy Yield in Bangladesh

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Abstract: In dry season paddy farming, the alternate wetting and drying (AWD) irrigation has the potential to improve water productivity and paddy production and decrease greenhouse gas (GHG), such as methane (CH_4) and nitrous oxide (N_2O), emissions when compared to continuous flooding (CF). Participatory on-farm trials were conducted from November 2017 to April 2018 in the Feni and Chattogram districts of Bangladesh. Total 62 farmers at Feni and 43 at Chattogram district, each location has 10 hectares of land involved in this study. We compared irrigation water and cost reductions, paddy yield, and CH_4 and N_2O emissions from paddy fields irrigated under AWD and CF irrigation methods. The mean results of randomly selected 30 farmers from each location showed that relative to the CF irrigation method, the AWD method reduced seasonal CH_4 emissions by 47% per hectare and CH_4 emission factor by 88% per hectare per day. Moreover, the AWD decreased the overall global warming potential and the intensity of GHG by 41%. At the same time, no noticeable difference in N_2O emission between the two methods was observed. On the other hand, AWD method increased paddy productivity by 3% while reducing irrigation water consumption by 27% and associated costs by 24%. Ultimately it improved water productivity by 32% over the CF method.

Keywords: methane; nitrous oxide; global warming potential; water productivity; paddy yield

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1. Introduction

Rice (*Oryza sativa* L.) is the fundamental food to Bangladesh's survival. It is the primary source of nourishment for 165 million compatriots and accounts for over 95% of the entire agricultural output of the country. Around 11 million hectares (75%) of the country's total cropped land is devoted to rice production, providing approximately 34 million tons of paddy rice [1]. The early monsoon *Aus* (upland rice), the monsoon *Aman* (wet season rice), and the dry winter *Boro* (Rabi/dry season rice) are the three seasons in which rice is farmed. Among the 316 cropping patterns in Bangladesh, rice-based patterns accounted for 51% of the net cropped area, with *Boro*-Fallow-*Aman* accounting for 27% [2]. *Boro* rice is typically planted in November–December and harvested in late April–early May in properly irrigated conditions due to very little rainfall in this season. Both *Aus* and *Aman* rice are mainly rainfed, covering 9 and 30% of rice land area, respectively. Currently, *Boro* rice has expanded to 61% from 9% in 1966–67 of the total cropped area, contributing 55% to total rice production [3]. Such expansion is mainly attributed to the advent of the use of fertilizers and shallow water pumps. Fertilizer (both organic and chemicals) accounts for more than half of global grain production, which provided 47% of total rice production in *Boro* and 26% in *Aman* seasons. The N fertilizers contribute 23 and 14% to total rice yield, while P and K contribute 9 and 15%, and 5 and 6%, respectively, in *Boro* and *Aman* seasons [4]. Due to the impact of traditional beliefs and a lack of sufficient information and scientific advice, many farmers over-fertilize croplands with N fertilizers, which is often regarded as a major contributor to N_2O emissions. Additionally, farmers are using manures from cow dung, poultry litter, compost, bio-slurry, municipal, and vermicompost, which all contribute to increasing the amount of CH_4 emitted by rice fields [5].

Moreover, the expansion of *Boro* paddy cultivation necessitated extensive irrigation water consumption, leading groundwater tables to fall at a pace of 4 cm per year, resulting in a rising water shortage. Bangladeshi farmers are now spending roughly 30% of the entire cost of rice production for irrigation [6], which is mainly operated by irrigation pump owners. Typically, they offer irrigation water on a contractual basis for the duration of each season at a set cost. He determines the complete irrigation program independently. The owner begins irrigating farmers' fields in his command area on one side and proceeds serially from one plot to the next until he reaches the last plot. Generally, farmers want to save as much water as possible throughout their irrigation shift. Additionally, most farmers feel that maintaining standing water in rice fields at all stages/phases is necessary to guarantee a larger harvest. They are spending around 2500−5000 L of water to produce one kilogram of rice [7]. However, scientifically, this quantity of water is not required from a physiological standpoint as continuous standing water is only needed at transplanting, blooming and grain filling stage/phase to avoid water stress [8].

This usual approach of continuous flooding (CF) leads to substantial surface runoff, flow, and infiltration, accounting for around 80% of total water consumption [9]. By 2025, Asia's available water supplies per capita are anticipated to decrease by 15–54% from 1990 levels [10]. Like other rice-growing regions on the Asian continent, Bangladesh is already experiencing water constraints, which means farmers need water-saving technology to produce rice with less water [7]. Due to Bangladesh's frequent water shortages, particularly during the dry *Boro* season, sufficient water to irrigate rice fields is increasingly scarce. Additionally, due to global warming, severe changes in the pattern of precipitation and drought have become more prevalent in recent decades, posing a substantial danger to managing water for rice farming. The increased quantity of atmospheric greenhouse gases (GHGs) viz., CH_4 and N_2O is a significant contributor to global warming and climate change. Rice farming accounts for about 11% and 6% of global CH_4 and N_2O emissions, respectively [11], while in Bangladesh, it contributes 33% of agricultural GHG emissions [12]. According to Wassmann et al. [13], irrigated rice is the most potential source for emitting 70–80% of global $CH_{4,}$ followed by monsoon rice (15%).

The International Rice Research Institute (IRRI) developed an alternating wetting and drying (AWD) irrigation strategy price [14] to save water and mitigate the emission of CH_4 and N_2O in rice fields instead of continual flooding (CF). Compared to CF, AWD reduced CH_4 and N_2O emissions by 45–90% [15] and irrigation water usage by 15–35% without decreasing rice productivity [16]. Leaching losses of soil N may also be decreased by reducing the percolation loss of irrigation water in AWD [17]. AWD may increase the soil P status by increasing the number of aerobic microorganisms [18] and increasing organic matter content through earthworm activities [19]. This could lead to more robust root anchoring, better nutrient uptake, more productive tillers, and more grain production [20]. Apart from saving irrigation water by 70% and CH_4 emissions by 97%, AWD was rebuked for 33% yields loss while N_2O emissions were more than quadrupled [21].

As discussed, the disparate effects of AWD on irrigation water use, GHGs emissions, and grain yields underscore the importance of additional research to increase our understanding of the relationships between cultivation practices, local environments, rice growth, and GHGs emissions. This information will be essential in assisting agricultural extension agencies and smallholder farmers in implementing AWD. This on-farm study aimed to determine the prospective for AWD to reduce CH_4 and N_2O emissions and its effect on rice production and irrigation water saving in the farmers' rice fields at Feni and Chattogram district of Bangladesh.

2. Materials and Methods

2.1. Experimental Site and Season

An on-farm participatory research trial was conducted at a total of 20-hectares land, 10 hectares under 62 farmers' paddy fields at Fulgazi of Feni district (N: 22°53′38″; E: 91°32′5″) and 43 fields at Mirsharai of Chattogram (former name was Chittagong) district (N: 23°32′14″; E: 90°24′18″) of Bangladesh (Figure 1) during November 2017–April 2018. The locations have an average climate characteristic with an annual mean rainfall of 498 mm. Maximum rainfall occurs during July–September. The highest and lowest air temperature prevails at 40 and 24 °C, respectively. The paddy soil is classified as clay-loam and loam, respectively. The soil properties are listed in Table 1.

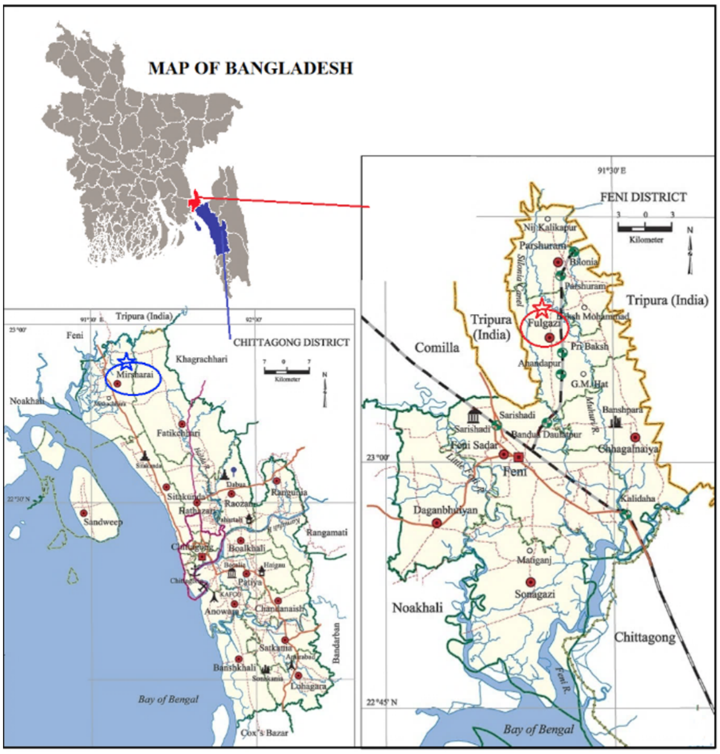


Figure 1. Locations of on-farm trials at Fulgazi, Feni, and Mirsharai, Chattogram, in Bangladesh.

Table 1. Chemical properties of soil (0–15 cm depth) at study locations.

Properties	Feni	Chattogram
pH	7.2	7.42
OM (%)	1.6	1.7
Total N (%)	0.13	0.14
Available P (ppm)	10.8	11.5
Available S (ppm)	77	82.8
Exchangeable K (Cmol kg^{-1})	0.16	0.18

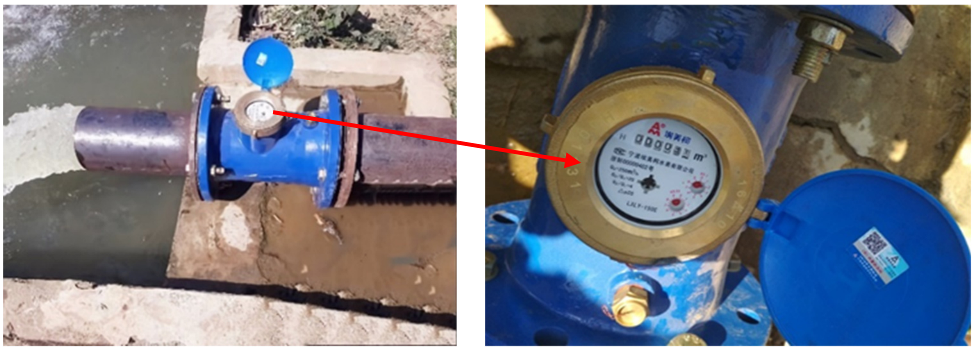
2.2. Land Preparation and Transplanting

A two-wheel tractor (2 WT) was used, including four rotary tillage passes and cross plowing, followed by two days of sun drying, and finally inundation and leveling. The fields were plowed and puddled thoroughly to about 10 cm depth before transplanting. Thirty-five days aged seedlings of BRRI dhan28 were transplanted at 20 cm × 20 cm spacing of rice hills to each plot.

2.3. Installation of AWD Pipes and Water Flow Meter

In each experimental field, 30 farmers' plots were selected randomly at a different distance from the water pump. PVC-made AWD pipes were installed 10 days after transplanting. We installed ten pipes in each bigha (1335 m^2) of land (Figure 2a). A farmer was treated as replication in every location with two treatments, such as AWD and CF (Continuous Flooding). We installed a water flow meter at the front of the outlet pipe of the irrigation pump (Figure 2b) to measure the amount of water and time to irrigate the field AWD plots.

(**a**)



(**b**)

Figure 2. (**a**) Installed AWD pipe in the field; (**b**) installed water flow meter.

2.4. Irrigation Management

Field plots under AWD were irrigated following the principles of 'safe AWD' [22], where floodwater depth inside the AWD pipes was monitored every day. Plots were re-flooded up to 5 cm from the soil surface when water depth dropped to 15 cm below the soil surface (Figure 3). AWD was suspended for 14 days (up to 20 DAT) after installing pipes to assist the suppression of weeds by the ponded water and improve the efficacy of herbicides (pretilachlor). Irrigation was stopped during the active tillering phase (20–40 DAT) to ensure the maximum tillers in each hill. Since then, AWD has been practiced up to 54 DAT. From one week before to one week after flowering (55–76 days after transplanting, DAT), a 2–5 cm water level was kept in the field. After flowering, during grain filling and ripening (77–100 DAT), the water level was dropped again to 15 cm below the soil surface before re-irrigation. In the CF irrigation method, fields were continuously flooded until two weeks before harvesting, and fields were irrigated regularly as and when needed. During the non-irrigation time, sufficient soil moisture was observed at the inner bottom of the AWD pipe. Moreover, slight precipitation of about 2.0 mm was recorded during 9–15, 86–89 and 96–100 days after transplanting (Figure 3), when the rice plant does not require any irrigation for growth and development.

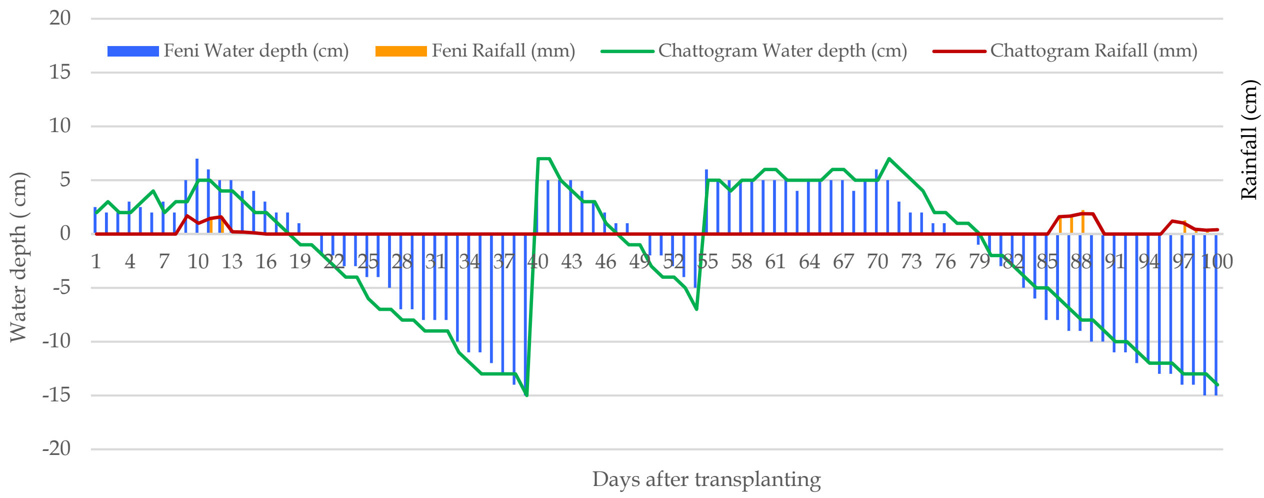


Figure 3. Schedule of AWD irrigation at different growth phases of rice.

2.5. Crop Management

2.5.1. Fertilizer Management

Fertilizer management was adopted as per government recommendation. Phosphorus (triple superphosphate) and potassium (muriate of potash) were applied during final land preparation at 85 and 150 kg ha^{-1}, respectively. Sulfur (gypsum) and zinc (zinc sulfate) were used to all plots as basal at the rate of 113 and 11 kg ha^{-1}, respectively. For nitrogen, prilled urea was applied as broadcast in three equal splits at 7–10 DAT, at maximum tillering and panicle initiation stages. The rate was 280 kg ha^{-1}. In this on-farm study, no organic manures were used. About 20% anchored residues of previous rice were incorporated during the final land preparation using a 2WT.

2.5.2. Cultural Management

Gap filling, weed control and insect and pest management were accomplished as per the guidelines of BRRI [23].

2.6. Measurements

2.6.1. Yield Attributes and Yield

Measurements such as crop growth duration (days), number of productive tillers m^{-2}, number of grains per panicle, 1000-grains weight (g) and grain and straw yield (t ha^{-1}) were collected. The crop harvested a physiological maturity (when 80% grains of a panicle became golden brown color) on 12 and 15 May 2018 in CF, while on 5 and 7 May 2018 in AWD at Feni and Chattogram, respectively. We reaped paddy from the central 2 m $\times$ 1.5 m area from three spots of each plot. The yield was calculated at 14% moisture content.

The growth duration (GD) was calculated based on the dates to maturity from the dates of seeding. Seeding was carried out on 21 December 2017 for both irrigation methods.

2.6.2. Greenhouse Gases (GHGs) and Other Indicators

i. The emissions of CH_4 and NO_2 were measured using the Cool Farm Tool Beta-3 (CFT) protocol [24].

ii. The global warming potential (GWP, kg CO_2 equivalent ha^{-1}) was calculated using the formula [25]: GWP = $CH_4 \times 28 + CO_2 \times 1 + N_2O \times 265$ (where, the amount of CH_4 and N_2O emission is kg ha^{-1} and CO_2 kg ha^{-1} over a 100-year time horizon)

iii. The intensity of greenhouse gas emission (GHGI, kg CO_2 equivalent ton^{-1}) was calculated using the following formula: GHGI = Total GWP/Grain yield [26].

2.6.3. Water Savings

The irrigation water savings were determined based on the numbers of required irrigation and the amount of water needed based on the readings of the water flow meter. All these measurements were carried out for both AWD and CF irrigation methods.

2.7. Data Analysis

Analysis of variance of the water productivity, paddy yield attributes and yield, cumulative seasonal emission of CH_4 and N_2O gases, GWP and GHGI was performed with the Statistical Tool for Agricultural Research: STAR 2.0.1 [27]. All pair-wise mean comparison of treatments was made with The Duncans' Multiple Range Test at a $p \leq 0.05$ level of significance.

3. Results

3.1. Water Productivity and Irrigation Cost

The irrigation method exerted a significant effect ($p \leq 0.05$) on the water productivity (WP) at both Feni and Chattogram locations of the study (Table 2). Data demonstrated that the frequency of irrigation per hectare of land was approximately 20 times lower in AWD (65 and 56 at Feni and Chattogram, respectively) relative to CF (85 and 73 at two locations, respectively). One hectare of land under the AWD method required a total of 3873 and 3382 m^3 of irrigation water at Feni and Chattogram, respectively. These amounts were 24% less than that of the CF method at both locations (5152 and 4454 m^3 ha^{-1}, respectively). At Feni, the WP of AWD and the CF method were 1.53 and 1.21 kg m^{-3}, respectively, while at Chattogram, the values were 1.84 and 1.36, respectively. On average of two locations, about 32% higher WP was estimated in AWD over CF. The mean values of WP for two locations revealed that AWD required about 592 L of irrigation water (excluding rainfall) to produce 1 kg paddy. On the contrary, CF required 807 L irrigation water. Hence, the water savings in AWD over CF is about 27%. Locally, the cost of single irrigation for one-hectare paddy incurred USD 6.5 (1 USD = 85.46 Bangladeshi Taka (BDT) as of 1 February 2022), the mean of two study locations incurred USD 513.5 in CF and USD 393.25 in AWD. Hence, AWD saved 24% of associated irrigation costs.

Table 2. Effect of irrigation methods on the water requirement and water productivity of paddy field in the Feni and Chattogram districts.

Irrigation Methods	**Number of Irrigations ha^{-1}**		**Amount of Irrigation (m^3 ha^{-1})**		**Water Productivity (kg m^{-3})**	
	Feni	**Chattogram**	**Feni**	**Chattogram**	**Feni**	**Chattogram**
Continuous flooding	85 a	73 a	5153 a	4454.5 a	1.21 b	1.36 b
Alternate wetting and drying	65 b	56 b	3873 b	3381.7 b	1.53 a	1.84 a
Co-efficient of variance (%)	31.35	25.71	31.64	28.80	10.95	9.81
Least significant variance ($_{0.05}$)	3.93	3.77	234.21	202.27	0.16	0.17
Standard deviation	23.52	16.60	1428.25	1128.66	0.57	0.61

Means with different letters indicate significant differences at the 5% level.

3.2. Yield Attributes and Yield of Paddy

Rice yield was influenced significantly ($p \leq 0.05$) by the irrigation methods at both the locations (Table 3) of the present on-farm study, which might have attributed to the significant variation of the number of productive tillers m^{-2} area. The AWD produced about 24% higher (1233 at Feni and 1311 at Chattogram) productive tillers relative to CF (979 and 1045 at two locations, respectively). In the present study, on average of two locations, we found about 3% higher paddy yield in AWD (5.96 and 6.24 t ha^{-1}) over the CF (5.78 and 6.06 t ha^{-1}). The number of paddy grains $panicle^{-1}$ and the weight of 1000-paddy grains did not vary significantly by the AWD and CF methods. The paddy under AWD matured about one week earlier than CF across the locations (Table 3).

Table 3. Effect of irrigation methods on the yield attributes and yield of paddy at Feni and Chattogram districts.

Irrigation Methods	Growth Duration (Days)		Productive Tillers m^{-2} (no.)		Grains per Panicle (no.)		1000-Grain Weight (g)		Grain Yield (t ha^{-1})	
	Feni	Chattogram	Feni	Chattogram	Feni	Chattogram	Feni	Chattogram	Feni	Chattogram
CF	142 a	145 a	979 b	1045 b	109	115	22.5	22.4	5.78 b	6.06 b
AWD	135 b	137 b	1233 a	1311 a	114	113	22.6	22.5	5.96 a	6.24 a
CV (%)	0.84	0.95	0.46	1.01	5.69	7.31	5.57	4.04	6.91	3.79
LSD $_{(0.05)}$	1.20	1.16	5.13	12.06	6.04	5.87	0.08	0.21	0.07	0. 08
Stdv.	5.30	4.99	129.60	137.01	19.52	18.33	0.32	0.24	0.44	0.25

CF: Continuous flooding; AWD: Alternate wetting and drying; CV: Co-efficient of variance; LSD: Least significant variance; Stdv.: Standard deviation. Means with different letters indicate significant differences at the 5% level.

3.3. CH_4 Emission

There was a significant effect ($p \leq 0.05$) of AWD and CF irrigation method on the emission of CH_4 gas from the paddy field at both on-farm study locations (Figure 4). A substantially higher total emission was usually found in CF, followed by AWD. We estimated 93 and 84 kg less CH_4 ha^{-1} in AWD at Feni (94 kg ha^{-1}) and Chattogram (107 kg ha^{-1}), which was about 49 and 44% smaller than that of CF (187 and 190 kg ha^{-1} at two locations, respectively). The data indicated the CH_4 emission factor for AWD was lower (0.74 kg ha^{-1} day^{-1}) than CF (1.39 kg ha^{-1} day^{-1}).

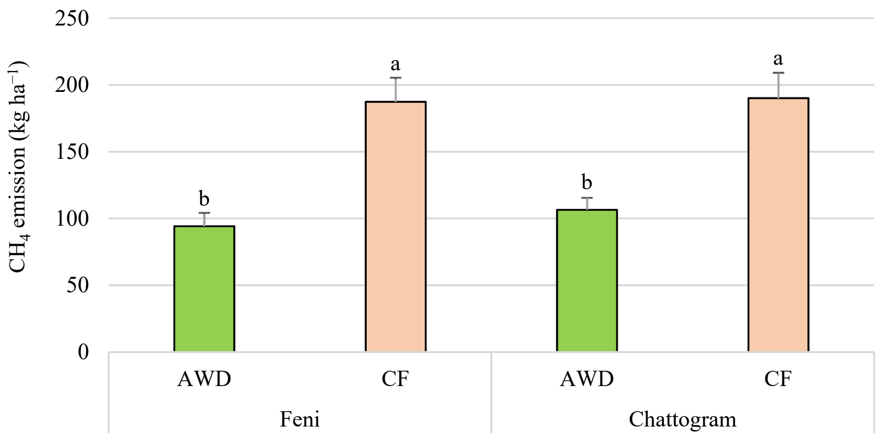


Figure 4. Effect of AWD and CF irrigation methods on the CH_4 emission from the paddy field at Feni and Chattogram districts. Means with different letters indicate significant differences at the 5% level.

3.4. N_2O Emission

The emission of N_2O did not vary significantly ($p \geq 0.05$) by the irrigation methods at both Feni and Chattogram (Figure 5). However, numerically, about 7% higher amount of N_2O was found in AWD both at Feni (10.7 kg ha^{-1}) and Chattogram (9.98 kg ha^{-1}) than that of CF (9.96 and 9.31 kg ha^{-1}, respectively).

3.5. The Global Warming Potential (GWP)

The GWP was affected significantly ($p \leq 0.05$) by the AWD and CF irrigation method at both locations (Figure 6). We found a higher share of GWP in CF than in AWD. The CF irrigation method produced 2232 kg higher CO_2 eq. ha^{-1} GWP at Feni (5435 kg CO_2 eq. ha^{-1}) and 2096 kg higher CO_2 eq. ha^{-1} GWP at Chattogram (5516 kg CO_2 eq. ha^{-1}) over AWD (3204 and 3420 kg CO_2 eq. ha^{-1}, respectively), which was about 70 and 61% higher than that of AWD at Feni and Chattogram, respectively. This data inclined about 41% reduction of GWP in AWD than CF. Overall, the total GWP attributed to CH_4 emissions was 95% in AWD and 97% in CF.

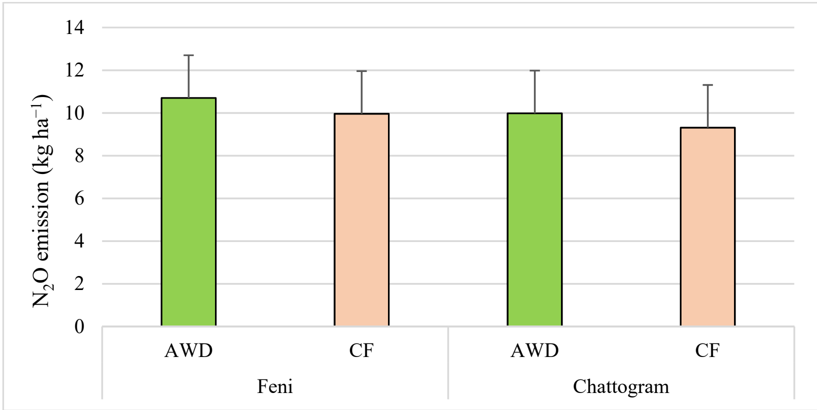


Figure 5. Effect of AWD and CF irrigation methods on the N_2O emission from the paddy field in the Feni and Chattogram districts.

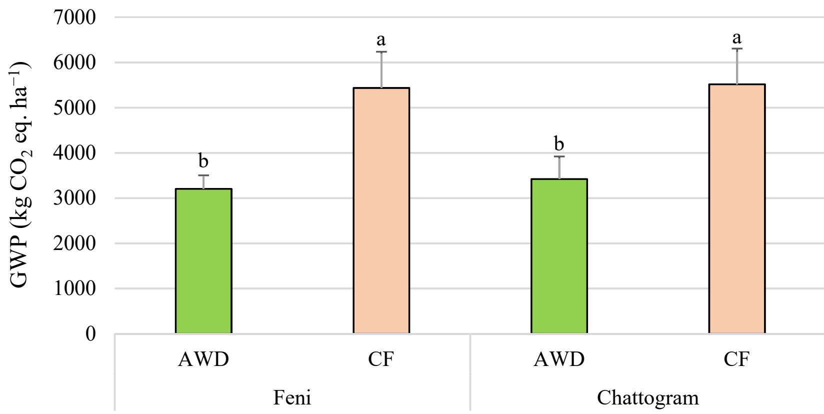


Figure 6. Effect of AWD and CF irrigation methods on the GWP from the paddy field at Feni and Chattogram. Means with different letters indicate significant differences at the 5% level.

3.6. The Intensity of GHG Emission (GHGI)

The impact of the irrigation method was significantly different ($p \leq 0.05$) on the GHGI at both Feni and Chattogram (Figure 7). We found that the GHGI of AWD was 42% and 40% lower at Feni (537 kg CO_2 eq. ton^{-1}) and Chattogram (546 kg CO_2 eq. ton^{-1}) than that of CF (940 and 910 kg CO_2 eq. ton^{-1}). Data revealed that the production of each ton of paddy under the AWD method attributed 537 kg of CO_2 at Feni and 546 kg of CO_2 at Chattogram. At the same time, CF was responsible for emitting 940 and 910 kg CO_2, respectively.

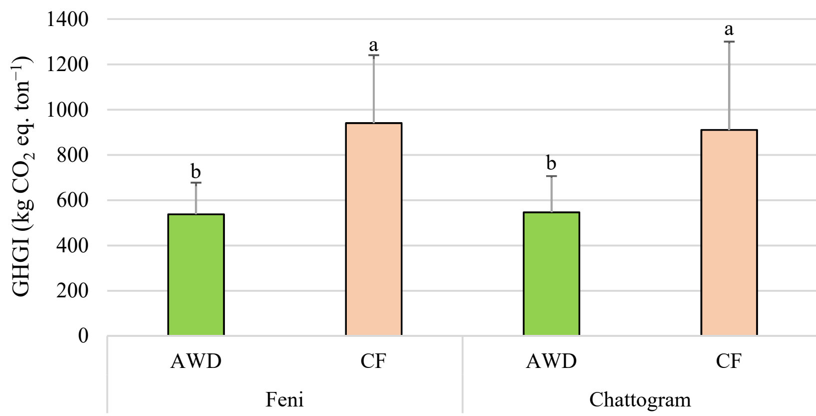


Figure 7. Effect of AWD and CF irrigation methods on the GHGI of paddy production in the Feni and Chattogram districts. Means with different letters indicate significant differences at the 5% level.

4. Discussion

4.1. Impact of Irrigation Methods on Water Productivity

AWD substantially ($p \leq 0.05$) increased the quantity and amount of irrigation water used (Table 2). Consequently, AWD (mean across locations, 1.69 kg m^{-3}) had a 32% greater water productivity than CF (1.28 kg m^{-3}). Therefore, water conservation is a significant advantage of AWD at this study location since it needed 20 less irrigation than CF. A similar conclusion was reached by Hossain et al. [28], who found that a season-long standing depth of water is not required for good rice yields and noted the highest 0.65 kg m^{-3} water productivity in AWD, while 0.35 kg m^{-3} in farmers' practice. Again, a past study by Anbumozhi et al. [29] showed an increase in water productivity of 1.26 kg m^{-3} in the AWD plot when compared to CF (0.96 kg m^{-3}). Feng et al. [30] concluded that AWD for rice should be more widely used due to its potential to increase water productivity by 19% in AWD compared to CF. By applying AWD, they found that irrigation water savings were 40–70% without any yield loss. Water conservation in AWD systems may be ascribed in part to decreased percolation and seepage. In this study, AWD used 25.7% less water on average than CF. AWD exposes fields to intermittent flooding (alternative cycles of saturated and unsaturated conditions), during which irrigation is stopped, and water is allowed to recede until the soil reaches a specific moisture level. At this point, the field is flooded. Compared to CF systems, AWD has been shown to minimize water inputs by 23% [31,32]. AWD substantially decreased irrigation water consumption by 34% [19] when compared to CF. Around 43% of water was found to be saved in AWD without compromising paddy yields [33]. Additionally, researchers observed irrigation water savings of 35% [34] and 30% [35] when AWD is used instead of CF. In AWD, percolation and seepage are substantially decreased, which improves water productivity by reducing the frequency of irrigation [19]. For example, in previous studies, 15−51% of total water input in a rice field was lost via percolation and seepage [15,36].

Saving about 27% of irrigation water resulted in a 24% reduction in irrigation expenses in our research. This result is consistent with earlier findings that AWD may help decrease irrigation expenses by lowering pumping costs and fuel usage [22]. Reduced irrigation was linked with a decrease in irrigation costs between 12 and 15%, indicating a significant benefit of AWD irrigation for resource-scarce farmers [37]. Additionally, Neogi et al. [6] projected a cost reduction of 35% with AWD irrigation over CF irrigation. Although the number of irrigations and related irrigation costs was significantly decreased in AWD, the benefits accrued directly to the pump owners due to the fixed-rate agreement reached the outset of the season between the pump owner and farmers. Under the AWD approach, farmers pay a fixed price per unit area regardless of the number of irrigations administered during the paddy growing season. To be benefited from the AWD technology in Bangladesh, a farmers' community-based, pre-paid card metering system of buried pipe irrigation scheme should be implemented.

4.2. Impact of Irrigation Methods on Paddy Yield

We observed a 3% increase in rice production in AWD compared to CF (Table 3), which may be attributable to a 24% in productive tillers. However, the number of panicles and the weight of 1000 grains were both constant numerically in AWD and CF. Increased paddy yields under AWD are primarily due to improved canopy structure and root growth with the decreased vegetative growth [38,39]; increases in abscisic acid levels during soil drying and cytokinin levels during re-watering; and enhanced carbon remobilization from vegetative tissues to grains [40,41]. Yang et al. [42] observed an increase in rice yields under AWD due to a rise in the percentage of productive tillers, a decrease in the angle of the uppermost leaves, which allows more sunlight to penetrate the canopy, and a shift in shoot and root activity. In Nepal, a group of researchers found no significant difference in rice yields between AWD and CF, with AWD saving 57% of irrigation water [43]. Rice fields with a 120–200 times greater soil oxygen content and more carbon release from the rice roots under AWD than under CF result in increased microbial populations and biomass in the rice rhizosphere and increased rice production [10,44]. The strong root development under AWD vs. CF more effectively absorbs water and nutrients, resulting in greater rice grain production [45]. Drying the rhizosphere modifies plant hormone signaling and increases grain filling rate [40]. The considerably greater number of productive tillers in AWD than in CF contributes to AWD's higher yield [43].

It is still disputed if the AWD irrigation system can reduce or sustain grain yields. AWD may result in increased nitrogen losses through nitrification and denitrification, reducing plant nitrogen uptake [46]. Increased tillers and effective tillers under AWD may have resulted in increased competition for plant resources between tillers and panicles, resulting in substantially reduced grain weight, quantity, and filling [47]. In comparison, a reduced tiller count under AWD was offset by increased grain weight and a higher percentage of grain filling per panicle, resulting in improved yield [31]. A meta-analysis of 56 research, including 528 side-by-side comparisons between AWD and CF, showed that AWD reduced rice grain production by 5.4% due to water stress [19]. However, Rahman and Bulbul [48] assert that a small amount of water stress on the plant does not reduce grain production. They found that water levels 15−25 cm below ground level in AWD had no effect on the total number of filled grains, while 5 cm standing water in CF did, and that such standing water throughout the season is not necessary for good rice yields. Additionally, certain research from southeast China indicates that using an AWD irrigation technique may improve grain production [38,39]. The factors outlined above may have increased paddy yield in AWD over CF in this research. The variations across research are due to differences in soil hydrological conditions and irrigation techniques used at different times [33]. This demonstrates the need for further research on the impact of AWD on rice production in Bangladesh.

4.3. Impact of Irrigation Methods on the Emission of GHGs and the Intensity of GHG

Irrigation methods under AWD and CF influenced the CH_4 emitted by rice production. In this research, AWD irrigation substantially ($p \leq 0.05$) decreased CH_4 emissions on average about 47% (49% at Feni and 44% at Chattogram) when compared to CF irrigation (Figure 4). These findings corroborate earlier findings [1,49]. When AWD irrigation is managed correctly, significant reductions in CH_4 emissions are anticipated. AWD's efficacy in lowering CH_4 emissions is dependent on the efficiency of water management, the kind of soil, and other cultivation techniques [50]. Soil methanotrophs break down CH_4 under intermittent aeration in AWD. This results in less CH_4 being released, which lowers the amount of CH_4 in the air. According to some estimates, up to 80% of the CH_4 generated during the rice-growing season is oxidized by methanotrophs [51]. In comparison, CF rice cultivation anaerobicifies the soil environment, lowering the redox potential, which promotes the anaerobic breakdown of complex organic substrates by methanogens, which ultimately results in CH_4 generation over AWD [52].

The methods of irrigation had no significant effect ($p \geq 0.05$) on the fluctuation of N_2O in this research (Figure 5). Although N_2O emissions from rice fields grown under AWD were about 7% higher than those from paddy fields cultivated under CF conditions in Feni and Chattogram. Changing water regimes to AWD influences the intensity of nitrification and denitrification, depending on the availability of oxygen. The topsoil layer becomes aerobic throughout a drying cycle, while the bottom soil layer stays anaerobic even when the water level reaches 15 cm below the soil surface. Thus, large amounts of N_2O are generated because of microbial nitrification of NH_4^+ and denitrification of NO_3^- [44]. While N_2O generation declines at very high moisture levels, it rises in fields with repeated wet and dry spells [53]. By contrast, some prior research indicates that CF enhances N_2O emission, and the higher the soil moisture, the larger the N_2O emission [54,55]. By contrast, the reduced N_2O emission peaks under CF conditions are most likely the result of additional denitrification to N under severe anaerobic conditions [56].

AWD irrigation reduced GWP by 41% as compared to CF irrigation. These results demonstrate that CH_4 emissions are completely responsible for the global warming potential of rice fields. Although N_2O has a much higher radiative force than CH_4, its emissions are insignificant. Thus, CH_4 is the main source of greenhouse gas emissions in rice cultivation, accounting for more than 90% of total GWP emissions [57,58]. In this study, the total GWP related to CH_4 emissions was 95% AWD and 97% in CF, while N_2O contributed only 1% to GWP. These results are consistent with previous studies [59,60]. As was previously observed for GWP, AWD irrigation showed the potential to reduce GHGI by 41% when compared to CF irrigation [18,61]. Therefore, the most successful strategies for lowering GWP and GHGI in rice production should focus on reducing CH_4 emissions.

5. Conclusions

We studied the efficacy of AWD in terms of water savings, paddy production, and GHG emissions in farmers' paddy fields at Feni and Chattogram districts in Bangladesh. The irrigation water consumption was significantly decreased by 27% in AWD with 32% greater water productivity. Hence, the irrigation costs were saved by 24% compared to CF. By this time, the paddy yield was improved significantly by 3% in AWD compared to CF. The AWD decreased seasonal CH_4 emissions by 47% than CF but did not affect seasonal N_2O emissions. Moreover, the AWD irrigation lowered the global warming potential and the intensity of GHG emission by 41% relative to CF. The simultaneous accomplishment of increased grain production, and water conservation, acceptable reduction of GHG emission is a prerequisite for AWD adoption by existing local farmers since water and environmental conservation are not reflected in the farmers' profit in the country. Field experiments demonstrating AWD's capability should be conducted in Bangladesh under a variety of agroecological zones, soil types, and farmer management circumstances. A community-based, prepaid card-metering subsurface irrigation system should be established to make AWD profitable to farmers rather than pump owners.

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