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Impact of Different Water Management Regimes on the Growth, Productivity, and Resource Use Efficiency of Dry Direct Seeded Rice in Central Punjab-Pakistan

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Abstract: Dry direct-seeded rice has been shown to save irrigation water and labor. Nonetheless, irrigation management in dry direct-seeded rice has received very little attention. Here, we examined the potential of different irrigation regimes: aerobic rice (AR), alternate wetting and drying (AWD) and continuous flooding (CF) in dry direct-seeded rice cultivation on two rice cultivars (Pride-1 (hybrid indica) and NB-1 (inbred indica)). Growth, yield attributes, grain yield, total water input, water productivity and benefit cost ratio were measured. Our results showed that AR saved 11.22 and 28.40%, and 5.72 and 32.98% water compared with AWD and CF during 2018 and 2020, respectively. There was a significant difference in grain yield among treatments and cultivars. AWD and CF produced statistically same total dry weight and grain yield, while AR reduced the total dry weight by 31.34% and 38.04% and grain yield by 34.82% and 38.16% in comparison to AWD and CF, respectively, across the years. Except for 1000-grain weight and harvest index in AWD and CF, further differences in total dry weight and grain yield among irrigation treatments were primarily correlated with variations in yield attributes. Among the cultivars, hybrid rice performed better than inbred rice. Over the two-year period, hybrid rice increased total dry weight, grain yield, and water productivity by 9.28, 13.05, and 14.28%, respectively, as compared to inbred rice. Regarding water productivity (WP), the maximum percentage (40.90 and 26.53%) was recorded for AWD compared to AR and CF. Among cultivars, more water productivity (14.28%) was calculated for hybrid rice than inbred one. Chlorophyll and carotenoid contents, leaf area index and crop growth rate contributed to higher grain yield of hybrid rice under AWD and CF. In contrast to WP, the maximum benefit cost ratio was estimated to be higher for CF than that of AR and AWD. For the cultivars, the maximum value (2.26 in 2018 and 2.32 in 2020) was calculated for hybrid rice compared with the inbred one. In conclusion, these results suggests that AWD with maximum WP and CF with maximum BCR could be more efficient approaches than AR. Under CF, hybrid rice cultivars with higher yield and yield-related attributes, WP and BCR performed better.

Keywords: dry direct-seeded rice; continuous flooding; water productivity; benefit cost ratio

1. Introduction

Rice (*Oryza sativa* L.), is an important staple cereal crop and fulfills the dietary requirement for more than of half population globally [1]. In Asia, rice is cultivated in a total area of 158 million ha annually. Rice cultivation is mainly practiced as transplanting of nursery seedlings into the puddled soil. However, in the recent years, researchers are focusing on alternative rice cultivation methods owing to a shortage of irrigation water and labor with an increasing labor cost [2,3]. For example, in China prior to 2000 the rice crop was commonly planted by puddled transplanting method but, in 2015 about 30% of total rice cultivated area was replaced by direct seeded rice cultivation [4]. Direct seeded rice (DSR; both wet direct-seeded rice and dry direct-seeded rice) has been proposed as an efficient planting method to attain the high-water productivity under water scarce conditions. With respect to yield potential, DSR records similar or even more yield as compared with transplanting rice [5–7]. Dry direct-seeded rice cultivation has been identified as a more water- and labor-saving technique under DSR, as it cuts water and labor requirements by 50% [8]. Under dry DSR cultivation, seeds are sown in unsaturated soil or non-puddled soil. Dry DSR is often commonly grown in rainfed lowlands because it allows crop harvesting before the start of the dry season. Dry DSR has been successfully adapted in China, India, Thailand as well as in Latin America and Australia [3,9]. In the past few years, different studies were conducted on the yield and water productivity of dry DSR, and reported variable response depending upon cultivar and location [10,11]. For example, Dong et al. [12] and Kato et al. [13] reported more than 11 t ha^{-1} yield in dry DSR. During a study conducted in the USA, Stevens et al. [10] achieved 10.3 Mg ha^{-1} yield from dry DSR fields with a water input of 750 mm, which was much lower than transplanted flooded rice. Similarly, Katsura and Nakaide [14] reported more than 9 t ha^{-1} yield from dry DSR cultivated fields. In Jiangsu province China, Shi et al. [15] reported 8.4 t ha^{-1} grain yield with flush irrigation. In another study, Zhao et al. [16] reported higher grain yield (5.33%) with 50% less water consumption in dry DSR than transplanted flooded rice. As compared with transplanted flooded rice, the increased grain yield of 22% with reduction of water input by 6000 m^3 ha^{-1} was reported in dry DSR [17]. Liu et al. [11] reported water productivity ranged from 0.96 to 1.02 kg m^{-3} among flooding durations and different cultivars under dry DSR.

Variety selection has a great influence on rice yield under different irrigation regimes. De Datta et al. [18] reported that 6 varieties out of 30 demonstrated higher yield in alternate wetting and drying (AWD) than continuous flooding (CF). Additionally, Virk et al. [19] tested 37 inbred and 7 hybrid varieties under CF and AWD rice cultivation. Under AWD, yield reduction was varied from 6 to 26% for inbred varieties and from 3 to 23% for hybrids while, 17% of water used in CF was saved in AWD, and 6 inbred and 3 hybrid cultivars were well adapted to AWD conditions. According to these findings, genetic heterogeneity exists in rice cultivars to respond to AWD conditions. Based on an ideal type, the selection of suitable cultivar significantly contributed to increase the rice productivity. Rice cultivars with thick roots, lower panicle weights, and less tillers performed well under DSR [20]. In recent studies, the better performance (8–15%) of "super" hybrid varieties than inbred and ordinary hybrid varieties were reported [21–23]. Increased biomass and more grain yield of hybrid varieties was mainly due to the increased sink size, large and heavy panicles, and great canopy light interception [24,25]. More grain yield of "super" hybrid varieties was often recorded even under ample supply of water.

Improved water management during rice cultivation plays an important role in attaining more benefits. Different water saving irrigation techniques have been developed for agricultural system; in rice, AR and AWD techniques are more useful for the achieving the more benefits [26]. The AWD practice is being promoted by the International Rice Research Institute (IRRI) as a water-saving irrigation practice. Under AWD, fields are subjected to intermittent flooding periods (alternate cycles of saturated and unsaturated conditions) where irrigation is interrupted and water is allowed to subside until the soil reaches a certain moisture level, after which the field is reflooded. AWD has been reported as strategy to reduce the water input and improve the grain yield [27]. According to Bouman and Tuong [28], yield penalty was reported under AWD-irrigated rice compared with CF. Commonly, increased water productivity was reported in AWD with respect to total water used, as smaller yield reduction was reported than the water saved. As compared with anaerobic rice cultivation, reduced irrigation inputs, higher water use efficiencies, and total water productivity were reported under AR cultivation especially in South Asian countries [29]. Different irrigation management regimes have great effects on the productivity and sustainability of DSR cultivation system. In Pakistan, adequate irrigation needs sufficient freshwater capacity and well-established irrigation facilities in the main rice-growing areas. Therefore, the farmers are unwilling to take the risk to establish the rice crop under dry aerobic cultivation. It is assumed that modifying the irrigation management practices might be helpful to solve the issues (high infestations of noxious weeds, low water use efficiency, low productivity, and unsuitable ecotypes for AR cultivation) associated with the direct sowing of rice under aerobic conditions in Pakistan. The present study, therefore, was conducted to examine the effect of different irrigation regimes (direct seeded aerobic rice, direct seeded flooded rice, and direct seeded rice with alternate wetting and drying) on the growth, productivity, and resource use efficiency of dry DSR, and to study the suitability of rice ecotypes (hybrid indica and inbred indica rice cultivars) under different irrigation regimes.

2. Materials and Methods

2.1. Site Description

A two-year experiment was conducted in the field area during summer season from July to November in 2018 and 2020 at Ayub Agricultural Research Institute, Faisalabad (31.4041° N, 73.0487° E, 184 m altitude above sea level). Faisalabad is located in the central Punjab, Pakistan, between the Chenab and Ravi rivers and represents a typical region where water shortage problems would have severe effects on the production of major field crops. The climate of Faisalabad is semi-arid with very hot and humid summers and a dry cold winter. During the summer, mean maximum and minimum temperature, and yearly precipitation are recorded as 29 °C, 27 °C, and 300 mm, respectively. Four replicates of soil samples from 0 to 20 cm layer were collected in the start of July 2018 and 2020 for analysis the chemical properties of soil. The experimental soil had clay loam texture horizontally and silt in depth with pH of 8.32 and 8.31, ECe of 1.35 and 1.33 dSm^{-1}, organic matter of 0.61 and 0.60%, total N of 0.032 and 0.033%, available P of 22.60 and 22.63 mg kg^{-1}, and available K of 184.1 and 1.83.9 mg kg^{-1} during 2018 and 2020, respectively. During both growing seasons (2018 and 2020), weather data (daily maximum and minimum temperatures, total rainfall, relative humidity, and sunshine hours) were collected from a field observatory near the experimental site, and are represented in Figure 1.

2.2. Experimental Design

The experiment was set up in split-plot arrangement with three replications. The main plot had three irrigation regimes (direct seeded aerobic rice (AR), direct seeded rice with AWD, and direct seeded flooded rice (CF)). The two rice ecotypes: Pride-1 (hybrid indica) and NB-1 (inbred indica) were assigned to the sub-plots. To minimize the seepage between the main plots, double bunds were formed to prevent water flow between the irrigation treatments. During 2018, the first irrigation was applied 4 days after sowing (DAS) while the next irrigations were applied at 13 DAS, 18 DAS, and 23 DAS, respectively, to all the experimental units. During 2020, the first irrigation was applied just after sowing while the next irrigations were applied at 9 DAS, 17 DAS, and 22 DAS, respectively, to all the plots. After 28 and 26 days of sowing, treatments (different irrigation regimes) were applied to experimental unit during 2018 and 2020, respectively. For direct seeded AR (treatment I), irrigation was applied only as per requirement of the crop (3–7 days interval) to the specific experimental units. For AWD treatments (treatment II), the crop was irrigated in such a way that standing water should be maintained for a whole week, while after the flooding period (one week) the crop was subjected to dry condition for one week to create the alternate wetting and drying condition. For CF (treatment III) the crop was irrigated in such a manner that continuous flooding should be maintained for the whole growth season (till 90 DAS). For measuring the discharge from water course, a cut-throat flume was installed. The total water input for IR, AWD, and CF in 2018 and 2020 was 664.1 and 586.4 mm, 748.1 and 622.4 mm, and 928.1 and 874.4 mm, respectively across the cultivars. The schematic presentation of irrigation application as per treatment is shown in Figure 2.

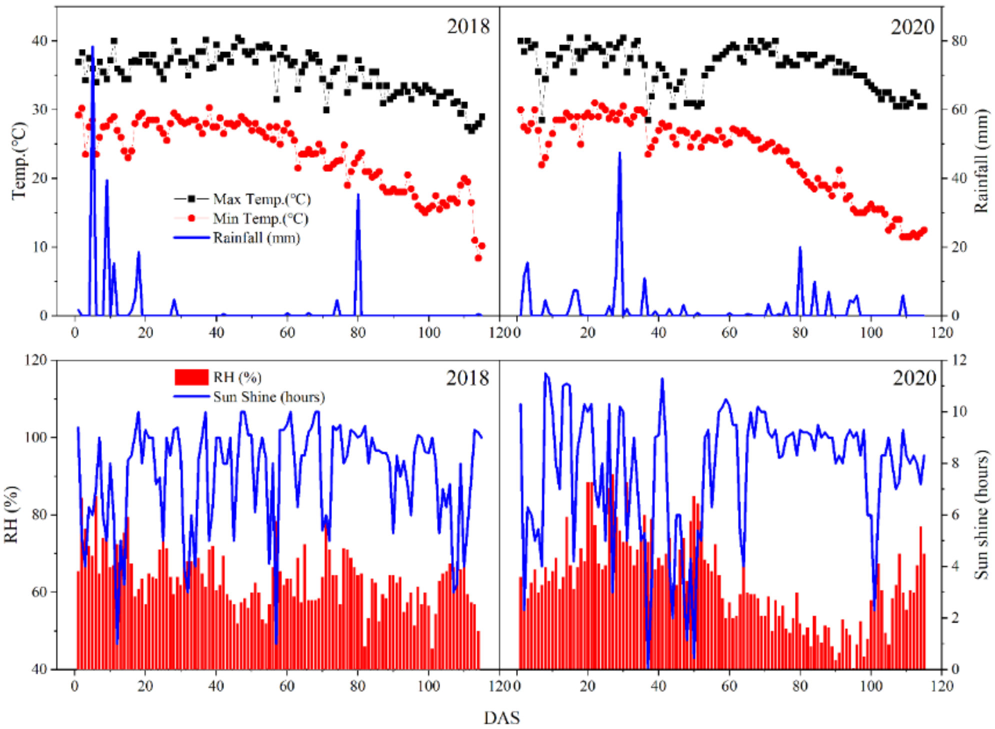

Figure 1. The average daily maximum (Max. Temp.) and minimum temperature (Min. Temp.), daily rainfall, relative humidity (RH, %), and sunshine hours at Faisalabad, Punjab province, Pakistan, from July to November (during rice growing season) in 2018 and 2020. DAS, day after sowing.

Both hybrid and inbred cultivars were sown on 12 July 2018 and 11 July 2020 under dry conditions, and each experimental unit had 20 planting rows (8 m length of each) with spacing of 15 cm at 3–4 cm seedling depth. In each plot, recommended nitrogen was applied into three splits: 33% at time of sowing and remaining was applied at tillering (20 DAS) and panicle initiation stage (70 DAS) in equal splits. The application of phosphorus (227 kg ha^{-1}, from Diammonium Phosphate) and potash (98 kg ha^{-1}, from Murate of Potash) were performed at the time of sowing while, zinc application (7.45 L ha^{-1}, from Zinc Sulphate) was done at panicle initiation stage. Fungicide was applied two times: one with Topsin-M (at panicle initial stage) and second with Karate (2.5 EC) at 40 DAS. Weeds were intensively controlled throughout growing season and no noticeable weed damage was observed.

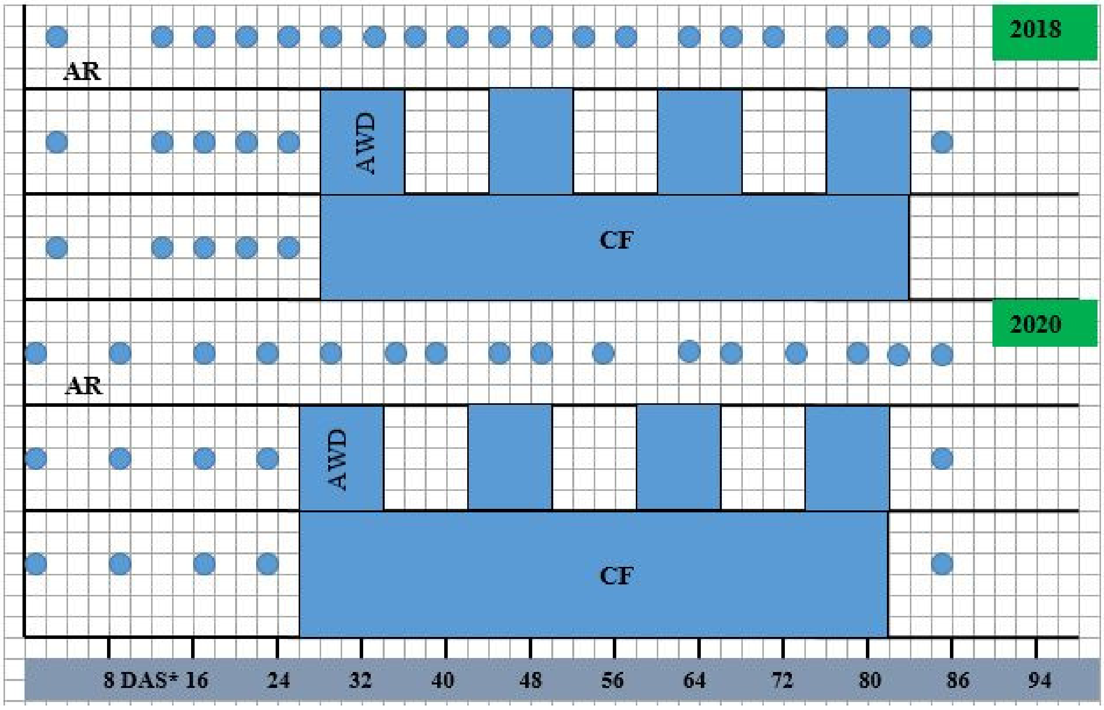

Figure 2. Implementation of the water regimes in dry direct seeded rice during the growth season of 2018 and 2020. Shaded area indicates the period of continuous flooding and dots donates the time of application of single irrigation. AR, aerobic rice; AWD, alternate wetting and drying; CF, continuous flooding. * days after sowing.

2.3. Harvesting and Data Collection

At tillering, panicle initiation, heading and grain physical maturity stage, 10 plants from each experiment unit were taken randomly to examine the plant height (cm), stem (including tillers) and panicle numbers (at maturity), leaf area index (LAI), crop growth rate (CGR), chlorophyll contents (Chl a & Chl b), and carotenoid contents at these stages and maximum values of these parameters were defined as the highest value across different stages. Chlorophyll and carotenoid contents were assessed spectrophotometrically as described by Peizhou [30]. Plant height was recorded from the soil surface to the panicle tip, while number of panicle (m^{-2}) was determined by direct count. Evaluation of spikelets panicle^{-1} was performed by randomly selecting 10 panicles from each plot. Grain filling percentage was computed as the percent of filled spikelets to the total number of spikelets (filled spikelets m^{-2}/total spikelets m^{-2} × 100). Productive tiller percentage (percent of productive tillers (m^{-2}) to maximum tillers m^{-2}) and harvest index (grain yield/total dry weight × 100) were also calculated. At maturity, grain yield was recorded by harvesting crop from 1 m^{-2} from each plot and corrected it to 14% moisture content. The 1000-grain weight (g) was calculated by weighing of four 1000-grain subsamples randomly collected from each plot. Water productivity was measured as grain yield divided by per unit of water input including both irrigation and precipitation. Benefit cost ratio was defined as the gross income per unit input cost including total fixed cost (land rent, tillage operations, transport charges, and expenditure on crop protection measures and harvesting) and total variable cost (seed cost and irrigation). Total income was calculated on the basis of per unit market price of grain and straw. Net returns were calculated by subtracting total expenditure from the total income.

2.4. Statistical Analysis

The means between irrigation regimes and cultivars were compared based on least significance difference (LSD) test at 0.05 probability level. Weather data graphs were prepared using the Origin-Pro software 2021.

3. Results

Summary of analysis of variance for different studied traits is presented in Supplementary Tables S1 and S2. Year as a factor did not influence all the studied traits, therefore, the data on the interaction of irrigation regimes and cultivars were presented.

3.1. Total Water Input

As compared to AWD and CF, AR saved water by 11.2 and 28.4% during 2018, and by 5.72 and 32.98% during 2020, respectively (Table 1). Under CF, hybrid and inbred cultivars consumed 26.40–45.05 and 30.20–53.24% more water than under AR, respectively across the years. Regarding cultivars, hybrid and inbred cultivars under AWD relatively consumed 4.09–9.70 and 8.19–12.60% more water than AR across two years. The amount of rainfall was 208.1 mm in growing season of 2018, and 202.4 mm in 2020 (Table 1).

Table 1. Irrigation times, irrigation, rainfall (mm), and total water input (mm, irrigation + rainfall) under different irrigation treatments and cultivars during growth period (2018 and 2020) at Faisalabad, Punjab Province, Pakistan.

Treatments	Cultivars	Irrigation Events		Irrigation Amount (mm)		Rainfall (mm)		Total Water Input (mm)	
		2018	2020	2018	2020	2018	2020	2018	2020
AR *	Hybrid	19	16	456	384	208.1	202.4	664.1	586.4
	Inbred	19	16	456	384	208.1	202.4	664.1	586.4
AWD	Hybrid	22	17	528	408	208.1	202.4	736.1	610.4
	Inbred	23	18	552	432	208.1	202.4	760.1	634.4
CF	Hybrid	29	27	696	648	208.1	202.4	904.1	850.4
	Inbred	31	29	744	696	208.1	202.4	952.1	898.4

* The treatments are: aerobic rice (AR), alternate wetting and drying (AWD), and continuous flooding (CF).

3.2. Plant Height and Yield Related Attributes

Irrigation treatments and cultivars significantly affected the plant height, number of panicles, and productive tillers during 2018 and 2020 (Table 2). Additionally, irrigation treatments significantly ($p \leq 0.05$) influenced the number of spikelets and grain filling percentage during both years of study; however, it had a non-significant impact on the 1000-grain weight. Similarly, cultivars significantly influenced the 1000-grain weight, while showing a non-significant influence on the number of spikelets and grain filling percentage during both years of study. The interaction of irrigation treatments × cultivars significantly influenced all the traits except for 1000-grain weight during both years of study. Among irrigation treatments, plant height, number of panicles, spikelets and productive tillers, and grain filling percentage were higher for AWD or CF relative to AR treatment. There was a non-significant difference between AWD and CF treatments, but AWD had more grain filling percentage during 2018 compared to CF. The plant height, number of panicles, productive tiller. and 1000-grain weight were significantly higher (0.38, 9.37, 8.35 and 5.32%) in hybrid cultivar as compared to the inbred one. Regarding treatments × cultivars interaction, hybrid under continuous flooding performed better, while inbred and hybrid under aerobic cultivation gave the lowest values of these traits (Table 2).

Table 2. Plant height, panicle m^{-2}, spikelets panicle^{-1}, productive tiller, grain filling percentage, and 1000-grain weight of hybrid and inbred rice cultivars under different irrigation regimes during 2018 and 2020.

Treatments	Plant Height (cm)		Panicle (m^{-2})		Spikelets (Panicle^{-1})		Productive Tiller (%)		Grain Filling (%)		1000-Grain Weight (g)	
	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
Irrigation Regimes (IR)												
AR *	90.00b	90.28b	287.00b	286.28b	124.38b	124.95b	53.01b	53.17b	58.53b	58.26b	23.58a	23.29a
AWD	103.57a	103.83a	320.92a	321.63a	135.98a	136.35a	78.38a	78.53a	75.35a	75.73a	23.67a	23.71a
CF	101.70a	101.95a	338.17a	338.81a	136.01a	137.88a	77.00a	77.14a	77.15b	78.23a	24.09a	23.94a
HSD ($p \leq 0.05$)	6.37	6.39	30.28	30.62	3.86	6.75	7.18	7.17	7.92	9.48	1.01	1.14
Cultivar (C)												
Hybrid (H)	98.60a	98.88a	328.72a	330.46a	132.63a	133.37a	72.20a	72.35a	71.23a	71.80a	24.37a	24.28a
Inbred (I)	98.24b	98.48a	302.00b	300.69b	131.60a	132.75a	66.73b	66.88b	69.46a	69.68a	23.19b	23.01b
HSD ($p \leq 0.05$)	4.22	4.23	20.75	20.31	2.56	4.47	4.76	4.76	5.25	6.29	0.67	0.76
IR × C												
AR × H	87.00c	87.30c	297.33b	298.05b	123.51e	121.90c	51.43c	51.53c	53.50c	52.73c	24.03ab	24.07ab
AR × I	93.00bc	93.27bc	276.67b	274.51b	125.25de	127.99bc	54.60c	54.76c	63.56bc	63.80bc	23.13b	22.51b
AWD × H	104.30ab	104.60ab	326.17ab	326.82ab	133.63bc	134.04ab	80.53ab	80.68ab	77.60ab	78.16ab	24.10ab	24.14ab
AWD × I	102.83ab	103.07ab	315.66ab	316.45ab	138.34ab	138.66ab	76.23ab	76.78ab	73.10ab	73.30ab	23.24ab	23.28ab
CF × H	104.50a	104.77a	362.67a	366.50a	140.75a	144.6a	84.63a	84.78a	83.60a	84.50a	24.98a	24.64a
CF × I	98.90ab	99.13ab	313.68ab	311.11b	131.20cd	131.60bc	69.36b	69.51b	71.73ab	71.97ab	23.20ab	23.24ab
HSD ($p \leq 0.05$)	11.39	11.42	55.90	54.72	6.90	12.06	12.83	12.82	14.16	16.95	1.81	2.04

* The treatments are: aerobic rice (AR), alternate wetting and drying (AWD), and continuous flooding (CF); Sharing the same small letter(s) do not differ significantly at $p \leq 0.05$. IR × C, interaction between irrigation regimes and cultivars.

3.3. Crop Growth, and Physiological Attributes

Chlorophyll a and b (Chl a and b), carotenoid content, maximum LAI and CGR were significantly ($p \leq 0.05$) influenced by the irrigation treatments, cultivars, and their interactions during both years (Table 3). The AR reduced the Chl a content by 24.84% and 25.30%, Chl b content by 39.21% and 36.73%, carotenoid content by 13.93% and 15.63%, maximum LAI by 7.11% and 8.33%, and CGR by 17.01% and 17.83% as compared to AWD and CF, respectively across the years. Although AWD and CF treatments were statistically the same, comparatively more Chl b and carotenoid contents were observed under AWD, and more LAI and CGR were recorded for CF. For cultivars, hybrid rice recorded higher Chl a, Chl b, carotenoid content, LAI and CGR by 20.14%, 6.97%, 12.55%, 4.46% and 17.32%, respectively, compared to inbred rice, across the years. Interaction of irrigation treatments × cultivars showed that hybrid rice either under AWD and CF gave the highest values of these traits during 2018 and 2020 (Table 3).

Table 3. Chlorophyll a and b, carotenoid, maximum lead area index (LAI) and crop growth rate for hybrid and inbred rice cultivars under different irrigation regimes during 2018 and 2020.

Treatments	Chlorophyll a (mg/g FW)		Chlorophyll b (mg/g FW)		Carotenoids (mg/g FW)		Maximum LAI		Crop Growth Rate (g/m^{2}day^1)	
	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
Irrigation Regimes (IR)										
AR *	1.26b	1.16b	0.32b	0.31b	6.72b	6.62b	6.90b	6.96b	6.72b	6.36b
AWD	1.70a	1.53a	0.52a	0.50a	7.79a	7.71a	7.44a	7.50a	7.79a	7.98a
CF	1.63a	1.60a	0.49a	0.50a	7.99a	7.87a	7.52a	7.59a	7.99a	7.93a
HSD ($p \leq 0.05$)	0.14	0.24	0.09	0.05	0.82	0.95	0.38	0.38	0.82	0.91
Cultivar (C)										
Hybrid (H)	1.67a	1.55a	0.45a	0.46a	7.95a	7.83a	7.45a	7.51a	7.94a	8.19a
Inbred (I)	1.39b	1.31b	0.44a	0.41b	7.05b	6.97b	7.13b	7.19b	7.05b	6.66b
HSD ($p \leq 0.05$)	0.09	0.16	0.06	0.03	0.54	0.63	0.26	0.25	0.54	0.60
IR × C										
AR × H	1.44b	1.24bc	0.28c	0.29d	6.57c	6.44c	6.87b	6.93b	6.57c	6.23b
AR × I	1.08c	1.08c	0.37bc	0.34cd	6.87bc	6.79bc	6.94b	7.00b	6.87bc	6.50b
AWD × H	1.75a	1.60ab	0.53ab	0.50ab	8.29ab	8.20ab	7.55ab	7.61ab	8.29ab	8.97a
AWD × I	1.66ab	1.46a-c	0.52ab	0.50ab	7.29bc	7.22a-c	7.34ab	7.40ab	7.29bc	7.00b
CF × H	1.82a	1.81a	0.55a	0.60a	8.97a	8.84a	7.93a	8.00a	8.97a	9.36a
CF × I	1.45b	1.40a-c	0.46a-c	0.40bc	7.01bc	6.89bc	7.12b	7.18b	7.01bc	6.50b
HSD ($p \leq 0.05$)	0.26	0.43	0.17	0.10	1.47	1.69	0.69	0.68	1.47	1.63

* The treatments are: aerobic rice (AR), alternate wetting and drying (AWD), and continuous flooding (CF); Sharing the same small letter(s) do not differ significantly at $p \leq 0.05$.

3.4. Yield, Harvest Index and Water Productivity

Results indicated that total dry weight, grain yield, and water productivity were significantly ($p \leq 0.05$) influenced by the irrigation treatments, cultivars, and their interactions during both years, except for total dry weight during 2020. Regarding irrigation treatments, AWD and CF produced statistically same total dry weight and grain yield while AR reduced the total dry weight by 31.34% and 38.04% and grain yield by 34.82% and 38.16% in comparison to AWD and CF, respectively, across the years. For water productivity, the maximum values were recorded for AWD, which was 40.90 and 26.53% more than AR and CF, respectively (Table 4). Between cultivars, hybrid rice performed better than inbred rice. On the average of two years, hybrid rice recorded higher total dry weight, grain yield, and water productivity by 9.28, 13.05, and 14.28% as compared to inbred rice. Under the interaction of irrigation treatments × cultivars, both rice cultivars either under AWD and CF produced the highest percentage of total dry weight, grain yield and water productivity during both years of study (Table 4).

Table 4. Effect of different irrigation regimes and cultivars on total dry weight, grain yield, harvest index and water productivity of dry direct seeded rice.

Treatments	Total Dry Weight (t ha^{-1})		Grain Yield (t ha^{-1})		Harvest Index (%)		Water Productivity (kg m^{-3})	
	2018	2020	2018	2020	2018	2020	2018	2020
Irrigation regimes (IR)								
AR *	5.74b	5.55b	2.75b	2.79b	47.88	50.54	0.41b	0.47b
AWD	8.23a	8.28a	4.21a	4.29a	51.15	51.94	0.56a	0.69a
CF	9.13a	9.09a	4.43a	4.53a	48.89	49.88	0.47b	0.51b
HSD ($p \leq 0.05$)	0.94	1.21	0.62	0.71	6.74	6.32	0.08	0.09
Cultivar (C)								
Hybrid (H)	8.08a	7.92a	4.01a	4.12a	49.88	52.56	0.51a	0.60a
Inbred (I)	7.32b	7.33a	3.58b	3.62b	48.74	49.01	0.45b	0.52b
HSD ($p \leq 0.05$)	0.62	0.80	0.41	0.47	4.47	4.19	0.05	0.06
IR × C								
AR × H	5.57c	5.16c	2.77b	2.80b	49.55	54.16	0.41b	0.47bc
AR × I	5.91c	5.95bc	2.73b	2.79b	46.20	46.92	0.41b	0.47bc
AWD × H	8.41b	8.45a	4.41a	4.54a	52.39	53.90	0.59a	0.74a
AWD × I	8.06b	8.11ab	4.02a	4.05ab	49.91	49.97	0.52ab	0.63ab
CF × H	10.28a	10.15ab	4.87a	5.02a	47.71	49.63	0.53ab	0.59a-c
CF × I	7.99b	8.03ab	4.00a	4.03ab	50.08	50.13	0.42b	0.44c
HSD ($p \leq 0.05$)	1.68	2.16	1.11	1.26	12.05	11.31	0.14	0.16

* The treatments are: aerobic rice (AR), alternate wetting and drying (AWD), and continuous flooding (CF); Sharing the same small letter(s) do not differ significantly at $p \leq 0.05$.

3.5. Benefit Cost Ratio

Benefit cost ratio (BCR) analysis indicated that hybrid cultivar under CF significantly increased the BCR during both years. The highest values of BCR (2.26 in 2018 and 2.32 in 2020) were obtained when hybrid rice was cultivated under CF condition followed by the order of: hybrid under AWD > inbred under AWD > inbred under CF > hybrid under IR > inbred under AR (Table 5).

Table 5. Influence of different irrigation regimes and rice cultivars on benefit cost ratio during both experimental years (2018 and 2020).

Treatments	Cultivars	Benefit Cost Ratio	
		2018	2020
Aerobic rice	Hybrid	1.29	1.29
	Inbred	1.11	1.14
	Mean	1.20	1.22
Alternate wetting and drying	Hybrid	2.04	2.10
	Inbred	1.63	1.64
	Mean	1.84	1.87
Continuous flooding	Hybrid	2.26	2.32
	Inbred	1.62	1.63
	Mean	1.94	1.98

4. Discussion

The present study demonstrated the effect of different irrigation regimes on the growth, productivity, and resource use efficiency of dry DSR. During the first year of study (2018), total water input was 12.34% higher than that of 2020 irrespective to irrigation treatments and cultivars. More water input during 2018 was mainly attributed to the less rain shower as compared to 2020 (Figure 1). Compared with CF, AR, and AWD with 10–12 fewer irrigations saved the water input. Singh et al. [31] found that AWD could save 40–70% of water compared with continuous submergence in transplanting rice. In another study, Yao et al. [32] reported 24–38% less water input in AWD compared with continuous flooding. Linquist et al. [33] reported 18–44% less water used under different AWD treatments as compared with CF treatment. According to Carrijo et al. [34], AWD can reduce the water demand by 23.4% compared to CF. Bouman et al. [35] concluded that CF is not more effective than AWD and AR, as it increases the seepage and percolation losses. However, in the present study, water saving under AWD was not as high as reported in previous studies, which might be due to high maximum temperature throughout the growing season (Figure 1). The water quantity for inbred and hybrid rice also differed, and results of this study indicate that overall water consumption of inbred cultivar was more compared with hybrid cultivar. Liu et al. [36] and Li et al. [37] also reported that hybrid rice has more ability to survive even under water shortage condition.

The total dry weight and grain yield significantly differed among irrigation treatments and cultivars (Table 4). Among irrigation treatments, AWD and CF produced statistically same total dry weight and grain yield while AR reduced the total dry weight by 31.34% and 38.04% and grain yield by 34.82% and 38.16% in comparison to AWD and CF, respectively, across the years. These results are in line with the findings of Linquist et al. [33], who reported similar yield under CF and AWD treatments (with 3–4 flooding events). In another study, Bouman et al. [35] also reported the similar yield trend in AWD and flooded rice. In our work, the better yield under AWD and CF treatments were mainly attributed to high values of yield contributing factors, including number of panicles and spikelets, grain filling percentage and thousand grain weight under these treatments, as compared to AR (Tables 2 and 4). Across the cultivars, hybrid rice performed better than inbred rice. On average of two years, hybrid rice increased the total dry weight, grain yield, and water productivity by 9.28%, 13.05%, and 14.28% as compared to inbred rice. Yuan [21] and Peng et al. [22] also reported 8–15% more yield in hybrid varieties compared with inbred and ordinary hybrid cultivars. Recently, Yao et al. [32] reported 26.5 and 21.5% more grain yield in hybrid rice under CF and AWD, than AR, respectively. Among the yield component, more yield reduction under AR was mainly due to the smaller number of panicle m^{-2}, spikelets per panicle, and reduced grain filling percentage across the cultivars. These observations are consistent with the findings of Nguyen et al. [38], where the authors have reported the retarded rice growth under AR due to less availability of water. In the present study, a smaller number of spikelets per panicle under AR was mainly associated with less panicle m^{-2} (Table 3). Likewise, AWD and CF increased the plant height, maximum leaf area index, productive tiller percentage, total dry weight, chlorophyll a, chlorophyll b, carotenoid contents, and crop growth rate compared with AR. The importance of the number of panicle and total dry weight to yield stability was previously described by several authors [22,39]. The yield stability of hybrid rice under AWD and CF was mainly associated with more carotenoid contents and productive tiller percentage as compared with inbred one under same treatments.

In this experiment, WP was significantly higher in AWD compared with other treatments during 2018 and 2020. In comparison with CF, similar yield was achieved in AWD with an overall reduction in water use of 23.96%, and such reductions for AWD have been reported previously [33,40]. More water use efficiency with increasing the severity of AWD has been well reported in previous published study [33]. More WP of dry DSR cultivation as compared with transplanted flooded rice also reported elsewhere [11]. The findings indicating that more WP under AWD might be due to the influence of cultivars, however tremendous difference among AWD and CF did not exist. Considerable variations for WP also existed among cultivars. Hybrid rice cultivar achieved more WP under AWD and CF conditions as compared with inbred one. These findings are consistent with Liu et al. [11] who reported more potential for WP in hybrid rice cultivar. Bouman et al. [35] also reported that higher yield potential may lead to achieving the more WP in hybrid cultivars.

The maximum BCR was computed for CF compared with AWD and AR during 2018 and 2020, while for the cultivars, higher BCR was recorded for hybrid rice under CF and lower was recorded for inbred rice under AR. These findings are consistent with Ishfaq et al. [41], who reported that CF achieved maximum BCR, mainly due to the higher grain yield. Among the treatments, more grain yield under CF might be attributed to the higher values of BCR, while more grain yield and higher market prices for hybrid rice were mainly responsible for more BCR.

5. Conclusions

In conclusion, AWD and CF can be successfully adopted under dry direct seeded rice cultivation. In comparison to AR, AWD and CF not only increased the growth and physiological traits, but also improved the biological and grain yield during both years of study. However, water productivity was higher in AWD as compared to AR or CF. Hybrid rice cultivation under CF with more benefit cost ratio has been proved more acceptable under dry direct seeded rice cultivation. Increasing the chlorophyll and carotenoid contents, spikelets per panicle, total dry weight, and more productive tillers should be critical factors of breeding more productive cultivars for aerobic rice.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11061151/s1, Table S1: Analysis of variance regarding the effect of irrigation regimes and cultivars on yield and yield contributed attributes of direct seeded rice, Table S2: Analysis of variance regarding the effect of irrigation regimes and cultivars on chlorophyll and carotenoid content, leaf area index (LAI) and crop growth rate of direct seeded rice.

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