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ORIGINAL PAPER

Yield and water productivity of rice as influenced by responsive drip irrigation, alternate wetting and drying versus conventional flooding under silty loam soil texture

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Abstract: Rice is a semi-aquatic crop, thus demands waterlogged condition in root zone, hence farmers generally puddle the land before transplanting to control deep drainage losses, which is destructive to the soil physical, chemical and biological health. Addressing these issues, this research study evaluated the yield and water productivity (WP) benefits of rice (PK 1121) for the un-puddled alternate wetting and drying (AWD) and responsive drip irrigation (RDI) against the conventional flooding (CF) with puddling, as control during 2021, using randomized complete block design with three replicates. The results indicated significantly less ($p \leq 0.05$) irrigation application (76% < CF) but with larger (18%) yield trade-off for the RDI treatment. Although, the AWD treatment showed comparatively less water saving (32% < CF) but resulted relatively higher yield (4% > CF). Nevertheless, the WP of RDI was significantly higher (249% > CF) but reduction in irrigation application was the main contributor. In contrast, both higher yield and reduced irrigation contributed to the higher WP (52% > CF) of AWD treatment. The study shows the prospects of increased WP by AWD at convenience and less cost, than the RDI system for PK 1121 rice variety. However, increasing the water release capacity of RDI or using drought tolerant variety may increase the WP of rice under RDI system at no yield trade-off, which may be instrumental for growing rice without puddling in the water scarce areas of the country.

Keywords: *Oryza sativa* L., responsive drip irrigation, water productivity, microporous tube.

Introduction

Rice is a semi-aquatic crop (Predeepa-Javahar, 2013), thus requires water logged conditions for improved crop production. Therefore, generally water is kept standing for prolonged period. As the saturated hydraulic conductivity of soil ranges of 0.78 mm h^{-1} for clay, 18.6 mm h^{-1} for loam, and 114 mm h^{-1} for sand (Jarvis and Messing, 1995), therefore the standing water causes huge deep drainage losses.

To minimize the excessive deep drainage losses in rice, generally the seedbed is puddled by intensive cultivation and rotary hoeing under standing water condition. This practice produces a hard layer in the top 14-

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20 cm (Kukal and Aggarwal, 2003), which help in reducing the 40-60% deep drainage losses and leaching of nutrients (Aslam et al., 2002). However, the intensive tillage for puddling under wet soil condition destroy soil structure, soil fauna and biota, and negatively impact on soil fertility (Kirchhof et al., 2000). Moreover, the hard layer prevents the roots proliferation and active root zone depth, which can cause long-term residual effects and negatively impact not only on the standing rice crop yield, but also affect the following wheat crop yield (Kahlown and Azam, 2002).

The shallow puddled layer mostly works in isolation from the natural ecosystem and crop growth and yield rely on artificial inputs (nutrients, water, etc.), while regenerative and self-amelioration properties of soil through root channelling and biological decomposition of crop residues, and other organic materials are negatively impacted. Puddling and standing water also accelerate methane gas emission by the an-aerobic decomposition of organic matter. This practice is followed in the Indus basin for decades; thus, the soil fertility is extremely low evidence through the low levels of organic matter in the rice-wheat zone (Nawaz et al., 2019), thus impacting rice sustainability in Pakistan. Therefore, alternative solutions are urgently needed to reduce deep drainage losses without puddling and land degradation.

Increasing yield and reducing water input may enhance water productivity. Larger yield can be achieved through selection of high yielding rice variety and improved agronomic management, especially through the optimum supply of inputs. Water is one of the most abundantly used vital input for rice crop. According to Qureshi (2020), in Pakistan the surface water is not sufficient to meet the rice water demand, thus more than 50% groundwater is used to meet the crop water needs, which has significant economic and environmental implications.

Therefore, high yielding and drought resistant rice crop varieties and the use of high efficient irrigation system is urgently needed for profitable and sustainable rice production in Pakistan. Addressing these issues, three irrigation methods including un-puddled responsive drip irrigation (RDI), alternate wetting and drying (AWD), and conventional flooding (CF) with puddling, as control were evaluated using rice variety PK 1121. The RDI (Responsive Drip Irrigation, GrowStream™) is claimed as the world's only irrigation and fertigation system that uses organic chemistry to allow each and every plant to self-regulate its own water and nutrient delivery.

RDI is comprised of a microporous tube that responds directly to root signals, releasing water and nutrients at a variable flow rate to precisely meet each plant's individual needs. Therefore, the impact of different irrigation methods on rice crop yield and water productivity were evaluated.

Material and methods

Site description

The study was conducted during the summer season 2021, at the field station of Climate, Energy and Water Research Institute (CEWRI) at National Agricultural Research Centre (NARC) farm, located at 33° 40' 31" N, 73º 08' 15" E, and at an altitude of 498 m above mean sea level, Chak Shahzad, Islamabad, Pakistan. The soil properties at the commencement of field experiment are presented in Table 1. The weather data recorded during the rice growing period (June to November 2021) in the experimental area is presented in Table 2.

Table 1: Soil physical, chemical and hydraulic properties of top 30 cm layer (sampled at 15 cm interval) at the commencement of experiment

Soil physical properties		Soil chemical properties		Soil hydraulic properties	
Parameters	Mean ± SD (*n* = 6)	Parameters	Mean ± SD (*n* = 6)	Parameters	Values
Clay (%)	15.34 ± 1.31	pH	7.84 ± 0.11	WP (%)	12.40
Silt (%)	53.23 ± 1.98	EC (dS m^{-1})	0.44 ± 0.05	FC (%)	27.70
Sand (%)	31.43 ± 1.87	N (mg kg^{-1})	1.23 ± 0.79	SAT (%)	46.70
Bulk density	1.42 ± 0.13	P (mg kg^{-1})	4.78 ± 1.34	AW (mm m^{-1})	150.00
Soil type	Silty loam	K (mg kg^{-1})	78.75 ± 13.78	Ksat (mm h^{-1})	19.96

SD - standard deviation; WP - wilting point; FC - field capacity; SAT- saturation; AW - available water = FC – WP; Ksat - saturated hydraulic conductivity.

Table 2: Average monthly weather data recorded at experimental site located at CEWRI-NARC Islamabad, during the summer season 2021

Month	Tmin (°C)	Tmax (°C)	Humidity (%)	Wind (km day^{-1})	Rainfall (mm)	Pan evaporation (mm day^{-1})
Jun	22.43	36.80	55	54.22	102.34	6.85
Jul	24.39	34.81	75	46.07	272.75	5.24
Aug	22.90	34.32	76	53.90	144.26	4.63
Sep	22.80	33.53	78	42.54	107.65	4.21
Oct	15.00	29.13	75	36.01	204.56	3.02
Nov	7.30	24.63	68	18.04	0.00	1.89

Tmin - average minimum temperature, Tmax - average maximum temperature.

Experimental design and treatments

The experimental plot was comprised of nine blocks of 1.83 m x 2.44 m, with three blocks (replicates) for each treatment, in randomized complete block design. Three treatments were used, including: i) alternate wetting and drying (AWD), - with 20 cm row to row and 20 cm plant to plant spacing, water level fluctuates between +5 cm to -15 cm depth in a perforated pipe of 15 cm diameter inserted to 20 cm depth; ii) responsive drip irrigation system: three RDI pipes were laid underground at 25 cm depth below ground level and at 61 cm spacing, with two rows of rice crop planted over each lateral line at 20 cm row to row and 12 cm plant to plant spacing over each lateral line; iii) conventional flooding (CF) - control: flat basin, 20 cm row to row and plant to plant spacing with standing water. The number of nursery seedling per block was kept similar across all treatments. The different treatments and their replicates were separated by 150 cm compacted earthen bunds of 30 cm height, which served as buffer area for avoiding mutual interference of treatments.

Irrigation and field management practices

The experimental trial commenced on a fallow land and the land was prepared traditionally using deep cultivation and manual levelling. Irrigation of around 180 mm was applied on transplanting day and mild puddling was applied manually on CF treatment, while no puddling was done in AWD and RDI plots. Nursery sown on 15th June 2021 was transplanted in all three treatments on July 16, 2021. Similar irrigation regime of standing water was maintained for 19 days after transplanting in all treatments, before the treatments specific irrigation regimes were applied.

The irrigation application was managed through valve-controlled metered pipe flow with volume measured in m^3 using flow meter for each treatment. The irrigation was scheduled by keeping a constant soil water level of 5 cm while maintaining soil matric potential of -30 kPa (using tensiometer and water budget technique) for ensuring the root zone above field capacity throughout the growing period. Similarly, the irrigation application to AWD treatment was managed by maintaining a water level between +5 cm to -15 cm in a perforated pipe of 15cm diameter inserted in seed bed. A water tank of 60 L capacity was installed near each RDI treatment and all the time irrigation water availability in the tank at 2 m water head above the land surface was ensured. The RDI system allowed emitting irrigation water in response to soil water stress exerted by the drying root zone due to evapotranspiration use of the crop and there was no need to schedule irrigation manually.

The fertilizers were top dressed manually in all treatments at transplanting stage. Weeds were controlled using pre-emergence herbicides and manually during post emergence period. The stem borer and chewing insects were controlled using the Coragen® (FMC Chemicals (Pty) Ltd., Pretoria, RSA) and termites were controlled by the granules. The record of inputs (fertilizer, pesticides and herbicides) is presented in Table 3.

Table 3: Record of input applications to different treatments during the rice season 2021

S. No.	Treatment and input	Date of input application		
		CF	AWD	RDI
1	Nursery sowing date	15/6/2021	15/6/2021	01/6/2021
2	Date of transplanting	16/7/2021	16/7/2021	16/7/2021
3	Urea 125 kg ha^{-1}	16/7/2021	16/7/2021	16/7/2021
	Urea 125 kg ha^{-1}	16/8/2021	16/8/2021	16/8/2021
4	DAP 125 kg ha^{-1}	16/7/2021	16/7/2021	16/7/2021
5	Zinc sulphate	16/7/2021	16/7/2021	16/7/2021
6	Granules for termite	23/8/2021	23/8/2021	23/8/2021
7	Coragen® for stem borer	02/9/2021	02/9/2021	02/9/2021
8	Harvesting	29/10/2021	29/10/2021	29/10/2021

CF - conventional flooding; AWD - alternate wetting and drying; RDI - responsive drip irrigation; urea (46% N); DAP (18% N, 46% P_2O_5). The chemicals applied at recommended rates when fungus, stem borer and pests' attacks were visible on 5% at field scale.

AquaCrop model (FAO)

The AquaCrop model of Food and Agricultural Organization of United Nation (FAO) was used according to Steduto et al. (2009). The model structures the soil-plant-atmosphere system by incorporating water and nutrients in the soil, growth, development and yield in the plant and thermal regime, rainfall, evaporative demand and carbon dioxide concentration in the atmosphere. This model has been extensively used for simulating the attainable yield of herbaceous crops (Raes et al., 2009; Vanuytrecht et al., 2014), and did not need local calibration but some parameters must be fitted by user, which depends on location, crop cultivar, and management practices. The model was parametrized with the field measured data of soil (Table 1), climate (Table 2), crop (Table 4), irrigation, field management and default atmospheric CO_2 concentration.

The AquaCrop model was calibrated through correlation with field measured canopy cover, biomass and soil water content data on days 55, 90 and maturity using AquaCrop inbuilt statistical indicators (SI), including Pearson correlation coefficient (r) (Benesty et al., 2009) and Wilmott's index of agreement (d). The validation results are presented in Table 5.

Table 4: Rice crop phonological stages under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI)

S. No.	Description	CF	AWD	RDI
1	Max canopy (days)	39	43	42
2	Senescence (days)	90	86	81
3	Maturity (days)	106	106	106
4	Flowering starting (days)	77	75	76
5	Flowering period (days)	13	14	11

Table 5: Calibration of AquaCrop model with field measured canopy cover, biomass, and soil water content data using inbuilt statistical indicator (SI) of Pearson correlation coefficient (r) and Wilmott's index of agreement (d)

Description	SI	CF	AWD	RDI
Canopy cover	r	0.91	0.89	0.93
	d	0.88	0.92	0.90
Biomass	r	0.99	0.96	0.98
	d	0.92	0.93	0.95
Soil water content	r	0.92	0.93	0.94
	d	0.92	0.85	0.84

CF - conventional flooding; AWD - alternate wetting and drying; RDI - responsive drip irrigation.

The calibrated AquaCrop model was used for identifying the water balance (evaporation, transpiration, infiltration, deep drainage) and water productivity based on evapotranspiration (WP_{ET}).

Data recording

The soil moisture was regularly monitored using the tensiometers for ensuring the soil water did not fall below field capacity or matric potential of above 33 kPa. The soil moisture in the root zone prior to transplanting and first irrigation was recorded by gravimetric method through collection of core samples of known volume (98.2 cm^3) from 0-15, 15-30, 30-60, and 60-100 cm soil layers. The soil samples were oven dried for 24 h at 105°C after recording their wet weight. The soil moisture was calculated according to procedure described by Akbar et al. (2016).

Irrigation depth (ID, in mm) as per treatment specific irrigation schedule was applied using the valve controlled metered pipe flow, calculated using Equation 1.

$$\text{ID (mm)} = \frac{\text{Volume of water applied (m}^3\text{)}}{\text{Area of field to be irrigated (m}^2\text{)}} \times 1000 \quad (1)$$

The water productivity (WP), the physical or economic output per unit of water application (Veimrober Júnior et al., 2022), was calculated according to Equation 2. The irrigation input water productivity (WP_i) of the rice was calculated as the ratio between the total dry weight of paddy rice in kg to the gross irrigation water input (m^3) during the season, while evapotranspiration water productivity (WP_{ET}) was calculated as the dry weight of paddy rice to the water consumed in meeting the evapotranspiration demand of the crop.

$$\text{WP (kg m}^{-3}\text{)} = \frac{\text{Dry grain yield (kg)}}{\text{Water input (m}^3\text{)}} \quad (2)$$

The crop yield data were collected by using sample size of 1.0 m^2 (1 m x 1 m) for all the treatments. After collecting the samples were sun dried for seven days before threshing and the paddy yield was calculated in ton ha^{-1}. The straw and grains were carefully separated manually. Earlier, the number of total and productive tillers were counted at physiological maturity, total number of hills and tillers per hill within a 1.0 m^2 area were counted as described by Kar et al. (2018). Two samples' of 1000 grains per sample were collected from three replicates of all treatments, which were oven dried at 60°C for two days before noting the weight. Simultaneously, the average length of 20 panicles at harvest was measured with wooden scale. Ten randomly selected panicles from each sample were counted for number of filled and unfilled/sterile kernels using visual observation and feeling method of pressing between the thumbs.

The spikelet sterility was calculated as the ratio between the numbers of sterile spikelet per panicle to the number of total spikelet per panicle. As per details given by Steduto et al. (2009), the data of crop canopy cover were collected at critical phonological stages, and as described by Ishfaq et al. (2020). The crop maturity was confirmed when the 95% spikelet changed their color from green to yellow. The harvest index was calculated as the ratio between the grain yield (in ton ha^{-1}) to the total biomass (grain + straw, in ton ha^{-1}).

Statistical analysis

All the data were analyzed using Microsoft Excel 2007 spread sheet and inbuilt statistical commands and graphical display of results. All the data sets were checked for compliance with the underlying analysis of variance ANOVA assumption, before applying the statistical analysis of Tukey's (HSD) test at $p \leq 0.05$ to compare the treatments means and the differences among treatments means were indicated by standard error bars.

Results

Irrigation applications

The total seasonal, daily average and number of irrigation applications to different treatments are summarized in Table 6. The irrigation regimes were applied after 19 days of transplanting for crop establishment and weeds control. The irrigation depths applied during the first 19 days were 22, 31, and 77% of the total irrigations during the season to CF (conventional flooding), AWD (alternate wetting and drying), and RDI (responsive drip irrigation) treatments, respectively. The results showed that, the seasonal irrigation reduced in 32 and 76% to AWD and RDI treatments, respectively, in comparison to CF treatment.

Similarly, the average daily irrigations applications were 24 and 95% less for the AWD and RDI treatments in comparison to CF treatment, during the latter 87 days crop period. A total of 627 mm rainfall was recorded during 27 rainfall events, with average daily of 23 mm, monthly average of 157 mm $month^{-1}$ (with contributions of 27, 23, 17, and 33% in July, August, September, and October, respectively). The average daily evapotranspiration was around 4.0 mm day^{-1} during the crop season, which indicate that the RDI has fulfilled 100% of the evapotranspiration needs during the crop season, irrespective of the rice needs for a waterlogged condition in the root zone.

Table 6: Total seasonal, average daily and number of irrigation applications and rainfall during season 2021 of rice grown under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI)

Treatments	Total irrigation (mm)	Mean daily irrigation (mm)	Irrigation count (during 19 + 87 days)	First 19 days irrigations (mm)
CF	4702a	77	12 + 48	1015
AWD	3218b	58	12 + 38	1005
RDI	1110c	4	10 + 71	850

Different letters in the column (total irrigation) indicate significant differences between means at $p \leq 0.05$, according to the Tukey-test.

Growth and yield components of rice

The growth and yield components of rice for the three treatments are summarized in Table 7. The results showed 2 and 17% less crop height, 4% higher, 2% less panicle length, 10, 23% less tillers per hill, 37, 22% larger filled grains, 54, 28% less unfilled grains, 6% larger, comparable wight of 1000 grains and 25, 41% less dry biomass for the AWD, RDI treatments respectively, when compared with CF treatment.

Table 7: Growth and yield components of rice grown under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI)

Treatments	Length (cm)		Count		Grain/panicle		1000 grains weight (gm)	Biomass (ton ha^{-1})
	Crop height	Panicle	Tiller/ hill	Tillers m^{-2}	Filled	Un-filled		
CF	114.8a	25.2a	14a	348a	47a	15a	25.7a	20.60a
AWD	112.4a	26.1a	13a	314a	64b	7a	27.3a	15.43a
RDI	95.9b	24.8a	11a	266a	57b	11a	25.6a	11.82a

Different letters in the columns indicate significant differences between means at $p \leq 0.05$, according to the Tukey-test.

Water productivity

The grain yield, irrigation application, and water productivity (WP) based on irrigation water input is summarized in Table 8. The results showed 4% larger, 18% lower grain yield, 32, 76% less irrigation applications and 52, 249% larger WP for the AWD, RDI treatments than the CF treatment, respectively.

Table 8: Dry grain, irrigation, harvest index (HI), and water productivity (WP) based on irrigation water input (WP) of rice grown under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI)

Treatments	Dry grain (t ha^{-1})	Irrigation (mm)	HI (%)	WP (kg m^{-3})
CF	4.167a	4702a	20.29	0.089a
AWD	4.333a	3218b	28.11	0.135a
RDI	3.433a	1110c	28.53	0.309b

Different letters in the columns indicate significant differences between means at $p \leq 0.05$, according to the Tukey-test.

Water balance and productivity using AquaCrop Model

The water balance including details of profile moisture level, water input and output are shown in Table 9. The results indicated similar reference evapotranspiration (ET_0), 3% less, 31% more evaporation, 9, 21% less transpiration, 28, 71% less deep drainage, 15% larger and 11% less water productivity based on evapotranspiration (WP_{ET}) for the AWD and RDI treatments, respectively, when compared with CF treatment. The average seasonal profile water content of 100 cm layer was 4, 14% less for the AWD, RDI treatments, when compared with CF (376 mm) treatment.

The results of seasonal variations in daily evaporation losses for the different treatments are shown in Figure 1. The daily evaporation ranged from 0.4 to 6.8 mm (mean of 2.0 mm day^{-1}) for CF, 0.1 to 6.4 mm (mean of 1.0 mm day^{-1}) for AWD, and 0.8 to 6.4 mm (mean of 2.0 mm day^{-1}) for

RDI. The daily evaporation values have shown an average decrease of 39% for the AWD and average increase of 94% for the RDI treatment than the CF treatment on daily basis.

Table 9: Water balance (input/output) evaluation using AquaCrop model under conventional

Treatments	Irrig (mm)	ET_0 (mm)	Evap (mm)	Trans (mm)	Infil (mm)	Drain (mm)	WP_{ET} (kg m^{-3})	WP_b (kg m^{-3})
CF	4700	440	159	325	5329	5006	0.850	6.340
AWD	3218	440	154	297	3845	3583	0.980	5.197
RDI	1110	440	208	256	1737	1431	0.760	4.620

Irrig - irrigation; ET_0 - reference evapotranspiration; Evap - evaporation; Trans - transpiration; Infil - infiltration; Drain - drainage; WP_{ET} - water productivity based on evapotranspiration; WP_b - water productivity based on water balance.

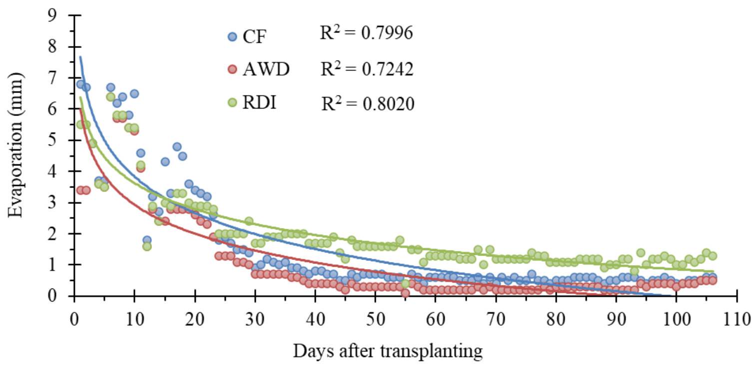

Figure 1: Variation in daily evaporation losses using AquaCrop model under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI).

The results of the seasonal variation in daily transpiration for the different treatments are given in Figure 2. The results showed daily transpiration in the range 0 mm to 5.6 mm (3 mm day^{-1} average) for the CF treatment, 0 mm to 4.9 mm (3 mm average) for the AWD treatment and 0 mm to 4.3 mm (2 mm day^{-1} average) for the RDI treatment. The daily transpiration values have shown an average decrease of 9% for the AWD and 15% less values for the RDI treatment, than the CF treatment on daily basis.

The details of water balance in rootzone profile including profile soil moisture, saturation, field capacity levels in 100 cm layer, irrigation and rainfall are presented in Figure 3. The results shows that the average root-zone profile 0-100 cm moisture content during the cropping season was 4 and 14% less for the AWD and RDI treatments, respectively, in comparison to CF treatment. The average profile moisture content remained 26, 23 and 15% higher than field capacity and 24, 30 and 44% lower than saturation for the CF, AWD, and RDI treatments, respectively.

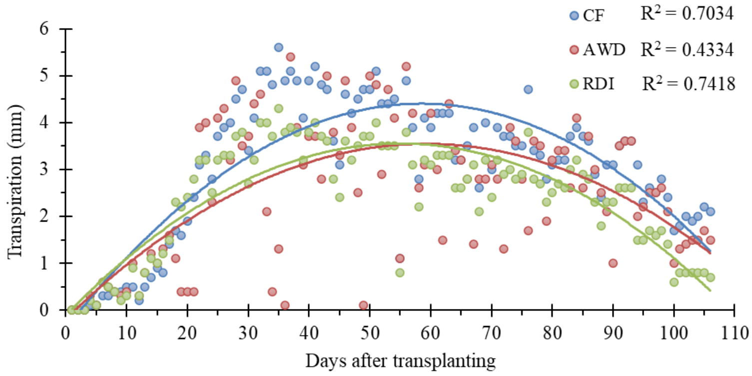

Figure 2: Seasonal variation in daily transpiration of rice using AquaCrop model under conventional flooding (CF), alternate wetting and drying (AWD), and responsive drip irrigation (RDI).

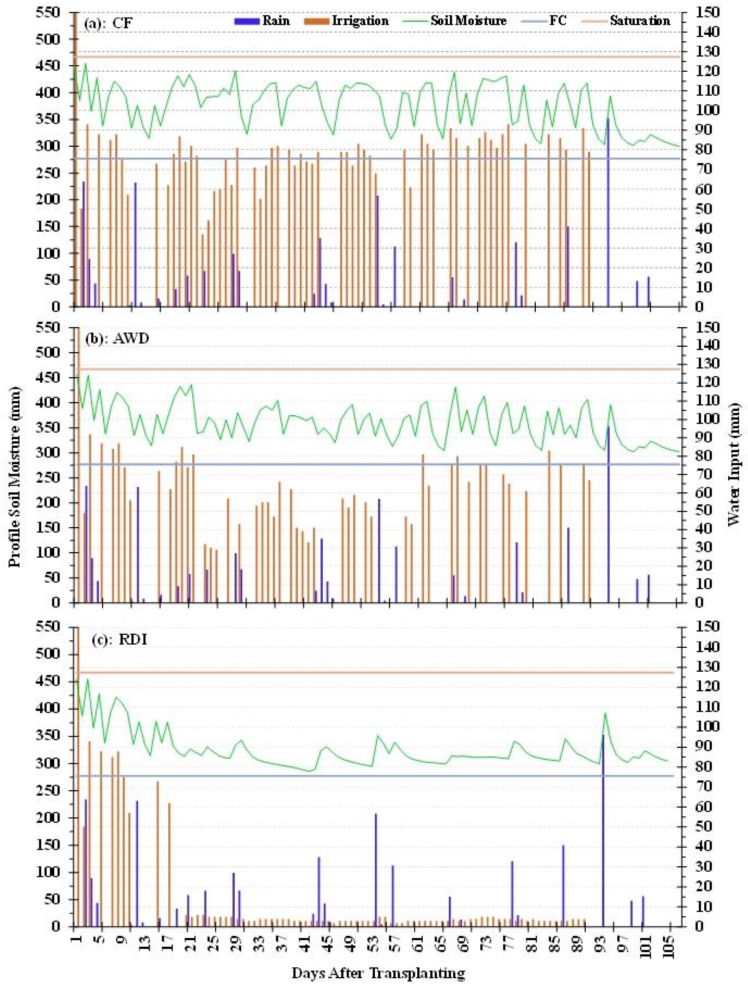

Figure 3: Water balance in root zone (0-100 cm) layer including profile soil moisture, field capacity, saturation, irrigation, rainfall using AquaCrop model under conventional flooding – CF (a), alternate wetting and drying – AWD (b), and responsive drip irrigation – RDI (c) during rice crop season.

Discussion

The irrigation application was significantly reduced to AWD (32%) and RDI (76%) treatments compared to the CF treatment (4700 mm), which followed similar trends as reported by Ishfaq et al. (2020), who also identified water saving with AWD method. However, the almost twice irrigation application to CF treatment compared with values of 2715 to 3125 mm reported by Ishfaq et al. (2020) can be attributed to the silty loam soil texture with higher saturated hydraulic conductivity, non-puddling and absence of hard pan in the current study.

The water saving of 76% by RDI with 18% yield tradeoff than the CF treatment indicates better performance than the findings of Ishfaq et al. (2020), who identified 50-55% water saving for the aerobic rice conditions, with yield trade-off of 32 to 37%. Moreover, the RDI performance is also comparable to the findings of Fawibe et al. (2020), who identified 70% water saving for rice but with no yield tradeoff under drip irrigation with plastic film mulching compared to CF treatment, and the reasons might be attributed to the changed environmental conditions and the different design of RDI microtube structure.

The grain yield of around 4.167 ton ha^{-1} for the CF treatment was 74% higher than the national average (2.5 t h^{-1}) during rice season 2020 (Pakistan Bureau of Statistics, 2020), and closely match the yield of hybrid rice reported by Hussain et al. (2021) on direct seeded rice from the central Punjab, Pakistan. However, the yield of rice in the present study is 38% less than the yield of Ishfaq et al. (2020). The reason for the less yield may be attributed to the varietal, growth and yield components (tillers' density and sterility) differences, as mentioned by Fawibe et al. (2020).

The higher yield for the AWD treatment can be attributed to the increased vigor (Carrijo et al., 2018; Parthasarathi et al., 2018) of frequent mild moisture stress, proliferation of roots to uptake more moisture and nutrients (Pascual and Wang, 2017), increased grain weight (Yang and Zhang, 2010), and reduced nutrients leaching (Rajwade et al., 2018), associated with less deep drainage losses (28%) compared to CF treatment. The lower yield (18%) for the RDI than the CF treatment may be attributed to larger water stress fluctuation to the level of above the threshold levels of rice variety (Singh et al., 2018), due to less seasonal wetting of root zone, remained 44% below the saturation, which may have impacted the crop growth and yield components as mentioned by Kruzhilin et al. (2017).

The water productivity (0.085 to 0.309 kg m^{-3}) agrees with the values (0.19 to 0.32 kg m^{-3}) reported by Jehangir et al. (2007), but significantly less than (0.32 to 0.732 kg m^{-3}) reported by Bakhsh et al. (2018), and the main reason is the larger irrigation application in the current study. The comparatively higher grain yield (4%) and relatively less (32%) irrigation application to AWD contributed in increasing the water productivity (52% AWD > CF), which conform to the findings of Joshi et al. (2009) and Liang et al. (2016), who concluded that increasing yield and reducing the water input increase the water productivity. However, the higher water productivity (249% > CF) for the RDI indicates the larger effect of reduced (76%) irrigation application, which defused the negative effect of reduced yield (18% < CF) on water productivity.

Conclusions

The alternate wetting and drying (AWD) method may increase yield (4%) and reduce irrigation water input (32%) without puddling and can easily be adopted at no cost.

The responsive drip irrigation (RDI) with no puddling can save irrigation water (76%) significantly but may reduce crop yield (18%) for rice (PK 1121) due to water stress, as the water release capacity of the microporous tube can moisturize the root zone (15% above field capacity levels) in silty loam soil, which may be suitable for most cereal crops, except rice. Therefore, growing rice crop with RDI demands for either increasing the water release capacity through changes in design of microporous tube or use of more drought tolerant rice variety.

The AquaCrop model is helpful in simulating the crop growth, water balance and productivity and assessing irrigation and field management strategies, which can be instrumental in improving the decision making for increasing the water productivity of rice.

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