Research Article

Water Productivity of Furrow, Drip and Flood Irrigated Rice under Loam Soil

Ghani Akbar*, Zafar Islam, Muhammad Umar and Shahi Salam

[1]*Climate, Energy and Water Research Institute, National Agricultural Research Centre, Park Road, Chak Shahzad Islamabad, Pakistan.*

Abstract | The low water productivity is making rice production unsustainable in Pakistan. Therefore, this study evaluated the water saving and productivity benefits of rice on furrow irrigated narrow beds (NB-65cm furrow spacing with 2 crop rows), drip irrigated wide beds (WB-130cm furrow spacing with 5 crop rows) and flood irrigated flat basin (FB) as control. The irrigation was scheduled at above field capacity (30kPa matric potential). The calibrated Aqua Crop FAO model was used for evaluating the root zone and atmospheric water balance and water productivity based on evapotranspiration (WP_{ET}). The field results indicated, comparable yield for the NB treatment but increased (2.4%) the water productivity based on irrigation input (WP_i), saved (3%) irrigation water and reduced (3%) deep drainage losses than the FB treatment. However, the WB treatment reduced (7.5%) crop yield, but increased the WPi (242%) and saved (73%) irrigation water. Thus, optimally managed furrow and drip irrigated raised beds can be helpful for the sustainable production of rice by reducing irrigation applications, eliminating the puddling and standing water under the conventional flat basin flooding method.

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***Correspondence** | Ghani Akbar, Climate, Energy and Water Research Institute, National Agricultural Research Centre, Park Road, Chak Shahzad Islamabad, Pakistan; **Email:** ghani_akbar@hotmail.com
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Introduction

Rice *(Oryza sativa)* is one of the three major cereal crops, affecting the livelihood and food security of around two-thirds of the world population. Rice is one of the most important cereal and cash crop of Pakistan. Pakistan is among the top ten (>7.5 million tons) rice producing (Irshad *et al*., 2018) and top five rice exporting (8.5% share) countries of the world. Thus, rice plays important role in earning foreign exchange to Pakistan (FAO, 2017). Basmati rice of Pakistan has huge exporting potential, because of its quality and aroma. The current average rice productivity (2.8 ton/ha) in Pakistan (GoP, 2017-18) is below global average and the main reasons are low yielding varieties, inappropriate farming methods for the site-specific conditions, lack of mechanized farming from sowing to harvesting and value chain issues. Moreover, the Basmati rice is mainly grown in saline/sodic lands in Pakistan (Qureshi *et al*., 2008), where other non-aquatic crops cannot be grown due to seasonal waterlogging, because of heavy monsoon rains during the season. Around 30% yield loss in the following wheat crop sown on flat is also compromised (Kahlown and Azam, 2002) due to impermeable saline/sodic soils, with poor soil structure and a hard pan created by the continues rice puddling for years.

Raised beds save water, energy, provide timeliness of operation, enhance yield, soil fertility, reduce soil erosion and facilitates mechanized farming (Akbar *et al*., 2016). Raised bed may partly store water on surface in furrows and provide more opportunity time for water to infiltrate and partly facilitate safe drainage, thus avoid crop yield loss due to seasonal submergence in standing rainwater (Akbar *et al*., 2007). Similarly, raised bed can diversify the crops in saline and waterlogged rice crop zones, where other non-aquatic crops are not possible due to standing water during monsoon period, thus making rice crop a compulsion and not a choice. Despite, all these benefits, growing rice and wheat on raised bed is scarce in Pakistan, while there is no comprehensive research undertaken to evaluate the production of rice on raised beds either furrow irrigated or drip irrigated without puddling and standing water. Keeping in view all these challenges, this study was formulated to assess the land and water productivity, water balance and water saving benefits for growing rice on furrow irrigated and drip irrigated raised beds compared to conventionally flooded and partially puddled flat basin irrigation methods.

Materials and Methods

Site description

The study was conducted at Climate, Energy and Water Research Institute (CEWRI) field station inside the National Agricultural Research Centre (NARC) farm, located at 33°40'31" N 73°08'15"E (498 masl) Chak Shahzad, Islamabad, Pakistan during the summer season 2020. 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 2020) in the experimental area is presented in Table 2.

Experimental treatments

Six times replicated sets of three treatments were laid in randomized block design, with a total of 18 equal size sub-plots of 10.5ft x30 ft size (29.28 m^2). The treatments were comprised of; i) Drip irrigated Wide Beds (WB) with 130cm furrow spacing and 15cm depth accommodating five rows of rice at 20cm spacing, ii) Furrow irrigated Narrow Beds (NB) with 65cm furrow spacing accommodating two rows at 20cm spacing and 15 cm depth, and iii) Flood irrigated flat basin (FB) after mild puddling as control with 20cm row to row and plant to plant spacing. The Super Basmati rice variety was used in the experiment.

Field management practices

The experimental trial commenced on a three years fallow land. The land was deep cultivated using disc plough followed by shallow cultivation and levelling with planking. Irrigation of 60 mm was applied before emplacement of the different treatments. The recommended dose of round up (Glyphosate) was sprayed at moist field condition. The different treatments and their replicates were separated by 10ft (300cm) wide compacted earthen bunds of 1ft (30cm) height, which served as buffer area for avoiding mutual interference of treatments.

The rice nursery was planted on same date of June 15, 2020 for all the treatments. The rice nursery was

Table 1: *Soil physical, chemical and hydraulic properties of top 15 cm layer at the commencement of experiment.*

Soil Physical properties			Soil Chemical properties			Soil Hydraulic properties	
Parameter	Average	SD	Parameter	Average	SD	Parameter*	Values
Clay (%)	19.92	1.91	pH	7.95	0.10	WP (%)	12.6
Silt (%)	49.44	2.77	EC (dS/m)	0.42	0.10	FC (%)	24.0
Sand (%)	30.64	2.47	N (mg/kg)	1.15	0.09	SAT (%)	46.0
Bulk Density	1.44	0.11	P (mg/kg)	4.66	1.51	AW (mm/m)	140
Soil Type	Loam		K (mg/kg)	79.17	20.98	Ksat (mm/hr)	18.6

**The abbreviations are 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 of Climate, Energy and Water Research Institute (CEWRI), National Agricultural Research Centre (NARC) Islamabad during the 2020.*

Month	*T min (°C)	T max (°C)	Humidity (%)	Wind (km/day)	Rainfall (mm)	Pan evaporation (mm/day)
Jun	22.20	36.20	48.18	65.63	62.92	6.68
Jul	24.32	35.81	59.37	60.03	175.07	5.54
Aug	24.45	32.81	78.45	40.05	359.16	4.12
Sep	20.70	33.43	63.30	20.08	53.64	4.04
Oct	13.13	31.61	47.40	20.46	0.00	3.63
Nov	8.00	22.50	64.33	19.48	90.67	1.74

**Tmin = Monthly average minimum temperature, Tmax = Monthly average maximum temperature.*

Table 3: *Record of input applications to different treatments during the rice season 2020.*

S. No.	Input	Date of input application (dd/mm/yy)		
		*FB	WB	NB
1	Nursery sowing	15/6/2020	15/6/2020	15/6/2020
2	Date of transplanting	15/7/2020	15/7/2020	15/7/2020
3	Urea (46% N) -80 kg/ha	15/7/2020	15/7/2020	15/7/2020
	Urea (46% N) -120 kg/ha	30/8/2020	30/8/2020	30/8/2020
4	DAP (18% N, 46% P_2O_5)-60kg/ha	15/7/2020	15/7/2020	15/7/2020
5	MOP (60% K_2O)-40kg/ha	15/7/2020	15/7/2020	15/7/2020
6	Roundup (Glyphosate)	01/6/2020	01/6/2020	01/6/2020
7	Carbofuran pesticide	15/8/2020	15/8/2020	15/8/2020
8	Recado™ fungicide	10/9/2020	10/9/2020	10/9/2020
9	Chlorpyrifos	25/9/2020	25/9/2020	25/9/2020
10	Harvesting	30/11/2020	30/11/2020	30/11/2020

**FFB= Flood irrigated flat basin, WB= Drip irrigated wide bed and NB = Furrow irrigated narrow bed. The chemicals applied when fungus, stem borer and pests' attacks were visible on 5% at field scale.*

planted on a well pulverised levelled plot. The six plots for the transplanted treatments were soaked one day before transplanting and the plots were mildly puddled manually. The nursery of one-month-age was transplanted on July 15, 2020 for all the treatments.

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 at soil matric potential of 30kPa (using tensiometer and water budget technique) for ensuring the root zone above field capacity throughout the growing period.

The fertilizer application was top dressed manually in all treatments at sowing and transplanting. Weeds were controlled using pre-emergence herbicides and manually during post emergence period. The stem borer and chewing insects were controlled using the Carbofuran and the bacterial and fungi infections were controlled by the Recado and Chlorpyrifos using manual spray pump. Similar, input of fertilizer, pesticides, and herbicides were applied to all treatments, as presented in Table 3.

AquaCrop model (FAO)

The Food and Agricultural Organization of United Nation (FAO) developed the AquaCrop model for simulating the attainable yield of herbaceous crops, which has been used in many studies (Steduto *et al*., 2009; Vanuytrecht *et al*., 2014). AquaCrop 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 (Steduto *et al*., 2009). AquaCrop did not need local calibration but some parameters depend on location, crop cultivar, and management practices, thus must be fitted by the user (Raes *et al*., 2009). AquCrop offers balancing accuracy, simplicity and robustness.

The AquaCrop model was parameterized with the weather data (Table 2) and default atmospheric CO_2 concentration. The crop phonological stages (Table 4) and field observed conditions were fitted in the crop file. Field measured practices and irrigation record of all treatments were separately fitted into field management and irrigation files. The soil data in Table 1 were fitted into the soil file.

Table 4: *Crop phonological stages for the different treatments.*

SN	Description	FB	WB	NB
1	Max canopy (day)	50	64	65
2	Senescence (day)	140	143	144
3	Maturity (day)	169	169	169
4	Flowering starting (day)	117	118	120
5	Flowering period (days)	25	25	25

FB= Flood irrigated flat basin, WB= Drip irrigated wide bed and NB = Furrow irrigated narrow bed

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), root mean square error (RMSE) and Wilmott's index of agreement (d).*

Description SI	SI	FB	WB	NB
Canopy Cover	r	0.99	0.97	0.97
	RMSE	3.00	5.30	3.80
	d	0.97	0.84	0.88
Biomass	r	1.00	1.00	1.00
	RMSE	0.90	0.70	0.90
	d	0.99	0.99	0.99
Soil water content	r	1.00	0.98	0.93
	RMSE	22.5	17.70	7.60
	d	0.82	0.80	0.68

FB= Flood irrigated flat basin, WB= Drip irrigated wide bed and NB = Furrow irrigated narrow bed

The AquaCrop model was calibrated through correlation with field measured canopy cover, biomass and soil water content data on day 40, 80 and maturity using AquaCrop inbuilt statistical indicators (SI) including Pearson correlation coefficient (r) (Benesty *et al*., 2009), root mean square error (RMSE) and Wilmott's index of agreement (d) and the validation results are presented in Table 5.

The calibrated AquaCrop model was used for identifying ET_0, evaporation, transpiration, infiltration, deep drainage and water productivity based on evapotranspiration.

Data collection

The soil moisture in the root zone was monitored by gravimetric method through collection of core samples of known volume (98.2 cm³) from 1-15cm, 15-30cm, 30-60cm and 60-100cm soil layers. The soil samples were oven dried for 24 hours at 105 °C after recording their wet weight. The soil moisture calculation was conducted according to Equation (1) (William and Whitman, 1969):

$$\theta_m = \theta_w \times 100/M_d \ldots\ldots 1$$

Where;

θ_m: Soil moisture content on a dry mass basis (%); θ_w: Mass of water within the soil sample (g); M_d: Dry mass of dry soil (g).

The bulk density of soil B.D. (g/cm³) determination was conducted as a ratio of dry soil mass (g) and soil sample volume (98.2 cm³) as per Equation (2):

$$B.D = M_d/V_b \ldots\ldots 2$$

Where;

B.D.: bulk density (g/cm³); M_d: mass of dry soil (g); V_b: bulk volume of soil sample (cm³).

The soil moisture on volume basis θ_v (cm) in a given soil layer was determined by multiplying the gravimetric soil moisture, soil layer depth and its bulk density as per Equation (3) (Dingman, 2002):

$$\theta_v = \theta_m \times B.D. \times d \ldots\ldots 3$$

Where;

θ_v: Volumetric soil moisture (cm); d: Depth of soil layer sampled (cm).

Irrigation depth in (mm) as per set irrigation schedule was applied using the valve controlled metered pipe flow. The irrigation volume for a treatment was calculated by multiplying the required depth in mm with the area of experimental treatment (m²), as presented in equation 4. The required volume of irrigation water was applied using the flow meter fitted into the delivery pipe.

$$Volume\ (m^3) = A \times D/1000 \ldots\ldots 4$$

Where;

A: Area of field to be irrigated (m²); D: Irrigation depth (mm).

The water productivity (*WP)* is a generic term used for determining the physical or economic output per unit of water application (Purcell and Associates, 1999). The gross irrigation water productivity (WP_i) of paddy rice was determined 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 cubic meter for meeting the evapotranspiration demand of the crop during the season. The formula of *WP* calculation is given in equation 5.

Water productivity (WP) = Dry grain yield of paddy rice (kg)/Water Input (m^3) …. 5

The crop yield data were collected by using sample size of 1.0 m^2 (1m x 1m) for the FB treatment and 1.3 m^2 (1.3mx1m) for the WB and NB treatments, to ensure accommodating the whole bed width, while accounting for the un-cultivated furrow area. The biomass samples of given size were collected from two points of each treatment and were sun dried for seven days before threshing and the paddy yield was calculated in ton/ha. The straw and grains were carefully separated manually. The total and productive number of tillers was counted at physiological maturity for all treatments. The total number of tillers in DSR treatments in 1.3 m^2 and total number of hills and number of tillers per hill within a 1 m^2 area were counted as described by (Kar *et al*., 2018). Two samples' of 1000 grains collected from both sampling locations of all treatments were oven dried at 60°C for 2 days before noting the weight. The average length of 20 panicles at harvest was measured with wooden scale. Ten randomly selected panicles from both sampling locations from all treatments 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. The data of crop canopy cover as per details given by Steduto *et al.* (2009) were collected at critical phonological stages, as described by (Yoshida, 1981; Ishfaq *et al*., 2020). The crop maturity was confirmed when the 95% spikelet changed their colour from green to yellow. The harvest index was calculated as the ratio between the grain yield in ton/ha to the total biomass (grain + straw) in ton/ha.

All the data were analysed 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 $\alpha = 0.05$ probability level to compare the treatments means (Steel and Torrie, 1986) and the differences among treatments means were indicated by standard error bars.

Results and Discussion

Irrigation application and soil moisture variation

Irrigation applications to surface irrigated treatments were comparable (63 mm/event) but significantly larger than the drip irrigation. Conversely, the numbers of irrigations were the highest (62) for the drip irrigated wide beds. A total of 73% and 3% of irrigation water were saved by WB and NB treatments than the FB (5879mm) treatment, respectively.

Crop growth and yield components

The crop growth and yield components are summarised in Table 6. The grain yield was 7.5% less and comparable for the WB and NB treatments than the FB treatment, respectively. The dry biomass was 11% and 8% less for the WB and NB treatments than the FB (18.16 ton/ha) treatment, respectively. The sterility of spikelet was 22%, 25% and 26% for the FB, NB and WB treatments, respectively. The 1000 grain weight was 12.6% less and comparable for the WB and NB treatments, respectively than the FB treatment.

Water productivity

The water productivity based on irrigation water input (WP_i) showed 242% and 2.4% higher values for the WB and NB than flat Basin (FB = 0.045 kg/m^3), respectively (Table 7).

Water balance and productivity using AquaCrop model

The results of AquaCrop simulations (Table 8) indicated ET_0 and transpiration values were comparable across the treatments but evaporation values of FB were higher than the (WB and NB) due to larger canopy cover. The deep drainage loss was lower for the WB (71%) and NB (3%) than the FB treatment. The WP_{ET} was 4.7% less and 2.3% higher for the WB and NB than the FB treatment, respectively.

Irrigation application and water balance

The irrigation application per season for the FB

Table 6: *Crop growth and yield components of rice for the different treatments of water management technologies (SD stand for standard deviation).*

Treat-ment	Crop height (cm)	Panicle length (cm)	Tillers / m^2	Dry biomass (ton/ha)	Dry grain yield (t/ha)	Harvest index (%)	1000 grain weight (gm)	Filled grains per panicle	Unfilled grains per panicle
FB	108	24	282	18.16	2.66	15	22.3	94	27
SD	4.5	1.3	30.5	1.6	1.3	2.8	2.2	18.3	7.5
WB	84	22	275	16.12	2.46	15	19.5	82	29
SD	5.5	1.4	28.4	1.9	1.1	1.5	0.8	12.1	7.4
NB	85	23	275	16.76	2.63	16	22.3	85	28
SD	5.6	1.3	32.3	1.6	1.3	2.4	1.5	3.7	4.5

FB= Flood irrigated flat basin, WB= Drip irrigated wide bed and NB = Furrow irrigated narrow bed

Table 7: *Water Productivity based on irrigation water input (WPi) for the different treatments (Standard deviation in brackets).*

Treatment	Dry grain yield (ton/ha)	Irrigation (mm)	WPi (kg/m^3)
FB	2.66 *(1.3)*	5879 *(33)*	0.045 *(0.01)*
WB	2.46 *(1.1)*	1995 *(24)*	0.154 *(0.02)*
NB	2.63 *(1.3)*	5706 *(38)*	0.046 *(0.03)*

FB= Flood irrigated flat basin, WB= Drip irrigated wide bed and NB = Furrow irrigated narrow bed

(5879mm) was the highest, which is higher than the findings of (Ishfaq *et al*., 2020), who identified water input (2715 to 3125 mm) and the reason might be attributed to less puddling and soil texture differences in the current study. Moreover, the irrigation input was significantly reduced (73%) for the WB treatment compared to FB treatment, which closely agree to the findings of Bakhsh *et al*. (2018) and Ishfaq *et al*. (2020) but higher than the finding of (Saleem *et al*., 2020), who identified 15-20% water saving for the direct seeded than the transplanted treatments, which might be attributed to the absence of a stable hardpan and porous loam soil composition (Kalita *et al*., 2020) in the current study. But this water saving was achieved at significant grain yield trade-off (7.5% reduction) for the WB treatment. The reason for low yield with WB might be attributed to the less wetting of the centre of 130cm wide bed, as already demonstrated (Akbar *et al*., 2017) for wheat-maize cropping pattern under similar soil conditions. Contrary to majority of previous studies, which have shown saving in irrigation water to the extent of 50-55% for the Aerobic Rice conditions, with yield trade-off to the extent 32 to 37% (Ishfaq *et al*., 2020), this study has shown up to 73% saving in irrigation water coupled with only 7.5% yield trade-off for the drip irrigated WB treatment than the FB treatment, which conform to the finding of (Fawibe *et al*., 2020), who also identified no yield gain but up to 70% water saving with drip irrigation than the FB treatment. The reason for the relatively better performance of drip irrigation than the previous studies can be attributed to optimum root zone soil moisture content due to frequent small irrigation applications, which reduce soil moisture stress (Parthasarathi *et al*., 2018) and deep drainage losses (71%) compared to larger irrigation depth applications associated with conventional methods. The reduced drainage losses also control nutrient leaching (Rajwade *et al*., 2018), thus leading to increased grain yield of rice under drip irrigation.

Crop growth

The crop growth factors have shown reduced tillers density were slightly lower (2.5% each) than the FB treatment, which conform to the finding of (Ishfaq *et al*., 2020), but reduced crop height (21%, 22%), panicle length (4%, 8%), biomass (8%, 11%), 1000 grainsweight (0%, 13%) for the NB, WB treatments respectively, which conform to the finding of (Soriano *et al*., 2018).

Table 8: *Water Balance analysis of different treatments using AquaCrop Model.*

Treatment	ET_0 (mm)	Evaporation (mm)	Transpiration (mm)	Infiltration (mm)	Drainage (mm)	WP_{ET} (kg/m^3)
FB	578	234	389	6486	6019	0.430
WB	578	222	388	2203	1753	0.410
NB	578	235	380	6312	5853	0.440

FB= Flood irrigated flat basin, WB= Drip irrigated wide bed, NB = Furrow irrigated narrow bed, WP_{ET} = Water Productivity based on Evapotranspiration

Grain yield

The comparable yield for the NB and FB and significantly reduced yield for WB treatment is contrary to the findings of (Ishfaq *et al*., 2020). The reason for the lower yield on WB might be attributed to the reduced root zone wetting in the centre of bed middle due to reduced infiltration as reported by Akbar *et al*. (2017). Other reasons of reduced yield might be low chlorophyll content, stunting and larger electrolyte leakage (Jahan *et al*., 2014) under the WB treatment. The reason for the higher yield of FB treatment might be attributed to the larger number of tillers, long panicle length and longer crop height, which are consistent to the finding of (Fawibe *et al*., 2020), while the frequent application of smaller irrigation depth (18mm) under drip irrigation helped in reducing seasonal fluctuation of water stress above the threshold levels (Singh *et al*., 2018), thus increased water saving with less crop yield loss (Kruzhilin *et al*., 2017).

Water productivity

The water productivity based on irrigation (WP_i) was higher for the WB (242%) and NB (2.4%) than the FB and the reason may be attributed to lower irrigation water input, which conform to the findings of (Joshi *et al*., 2009; Liang *et al*., 2016), who concluded that increasing yield and reducing the water input increase the WPi. These ranges of WB treatment are in conformity with the WPi values (0.19 to 0.32 kg/m^3) reported by (Jehangir *et al*., 2007), but significantly lower than (0.32 to 0.732 kg/m^3) reported by (Bakhsh *et al*., 2018) and the reason was the reduced (50%) yield and higher irrigation application in the current study. The WP_{ET} was lower for the WB (5%) and higher for the NB (2.3%) treatment, when compared with the FB treatment and the reason might be attributed to lower yield (7.5%) but with less evaporation (5%), while comparable yield for the NB but with reduced transpiration (2.3%) than the FB treatment. These results are of significant importance for improving the lower water productivity of rice crops under traditional management practices.

Conclusions and Recommendations

- Drip irrigated wide bed saved maximum (73%) water with (7.5%) yield trade-off, thus can be helpful in reducing (75%) the deep drainage losses and increasing the water productivity (242%) without puddling and standing water, thus can be recommended under water limited conditions only.
- Furrow irrigated narrow beds may increase water saving (3%) at no significant yield trade-off (1%), thus can be better alternative option for replacing the traditional puddling and flooding irrigation methods at no significant cost, but require optimized irrigation and field management for improved performance under the site-specific field conditions.
- The calibrated AquaCrop model appropriately simulated the crop growth, water balance and water productivity, thus can be instrumental in improving the decision making for increasing the water productivity of rice.

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Novelty Statement

As far as the authors are aware, there is no similar research work that has explored alternatives and more resource efficient solutions compared to the traditional intensively tilled transplanted rice system in this ecology. We believe that the analysis, topics covered and implications of results presented are of significant importance and would be of particular interest to the readership.

Author's Contribution

Ghani Akbar: Conceived the idea, conducted literature review, synthesize the data, wrote the paper and presented the results, discussions and conclusions.
Zafar Islam: Supported in field experimentation and data collection.
Muhammad Umar: Supported in literature review, data collection and data compilation.
Shahi Salam: Supported in field data collection and data compilation.

Conflict of interest

The authors have declared no conflict of interest.

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