Research Article

Investigating effects of deficit irrigation levels and fertilizer rates on water use efficiency and productivity based on field observations and modeling approaches

Abstract

Investigating the effects of optimized fertilizer and irrigation levels on water use efficiency and productivity of wheat crop at small farms is of great importance for precise and sustainable agriculture in Pakistan's irrigated areas. However, traditional farmer practices for wheat production are inefficient and unsustainable. This study aimed to investigate the effects of deficit irrigation and nitrophos fertilizer levels on bread wheat grain yield, yield parameters, nutrient use and water use efficiencies in bed planting wheat compared to traditional farmers' practices in the flat sowing method. The two-year field experiment followed a randomized complete block design of three replications, taking three irrigation treatments according to the requirement of crop estimated by CROPWAT model (100% of ET_C), deficit irrigation (80% of ET_C), and deficit irrigation 60% of ET_C and three nitrophos fertilizer treatments (farmer practice 120 kg N ha^{-1}, optimized 96 kg N ha^{-1}, and 84 kg N ha^{-1}) at different growth stages. Crop ET_C was calculated using the FAO CROPWAT 8.0 model from the last ten years (2003-2013) average climate data of the experimental station. The traditional farmer practice treatment was included as a control treatment with a flat sowing method compared with other sown-by-bed planter treatments. All treatments were provided with an equivalent amount of fertilizer at the basal dose. Before the first and second irrigation, top-dressing fertilizer was used in traditional farmers' treatment at the third leaf and tillering stages. It was applied in optimized treatments before the first, second, and third irrigation at the third leaf, tillering and shooting stages, respectively, under the bed planting method. The deficit level of irrigation (80% of ETc) and optimized fertilizer (96 kg N ha^{-1}) showed the optimum grain yield, nutrient use, and water use efficiencies, with 20% reduced irrigation water and fertilizer levels than traditional farming practice. The results suggest that bread wheat should be irrigated with 80% of ET_C and applied 96 kg N ha^{-1} nitrophos fertilizer at the third leaf, tillering, and shooting stages to achieve higher grain yield and water and nutrient use efficiencies under bed planting.

Keywords: optimized treatments, split doses, CROPWAT, ETc, deficit irrigation, nutrient use efficiency, water use efficiency, irrigated areas, small farms, nitrophos fertilizer, water productivity

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Introduction

The agriculture sector plays a vital role in the agrarian-based economy of densely-populated Pakistan, contributing 18.9% to the Gross Domestic Product (GDP) and consuming 42.3% of the labor force.[1] In PakistLan, bread wheat (*Triticum aestivum L.*) contributes 8.9% to agricultural value-added and 1.6% to GDP. Meanwhile, it is the main staple food item and the widely used grain variety. The country's total wheat production was 25.190 million tons from 8,740 thousand hectares for the financial year 2019−20.[2] Given the developing economy and large population, sustainable and efficient production of wheat is necessary not only to support the economy but also to feed the ever-growing population.

In irrigated areas of Pakistan, bread wheat is planted using the drilling or spreading method in the Rabi season. Under the drilling method, seeds are drilled in rows while keeping a row-to-row distance of 22.5 cm.[3] The drilling method can be named bed planting when seeds are drilled on beds of specific geometry. The bed planting

technology is instrumental in saving water along with numerous other advantages, including enhanced fertilizer performance, uniform water distribution, lower lodging, better crop stands, natural excess water drainage after rain, simple weed control, and increased yield.[4–7] On the other hand, in the spreading method used by farmers, seeds are spread on the smoothed soil surface, followed by narrow cultivation. In Pakistan, wheat grain yield per hectare is still 65−70% lesser than that in other wheat-producing countries[3,8,9] even though farmers use excessive amounts of irrigation[10,11] and fertilizers to boost crop yield in flat sowing method.

Irrigation management problems are generally coupled with fertilizer management issues.[12] Improper fertilization and watering are the leading causes of nitrogen leaching, usually after the irrigation,[13,14] mainly when excessive irrigation water is applied.[15] High fertilizer levels, primarily synthetic fertilizer, are often used to achieve high yields and nutrient use efficiency (NUE); however, the increased application of fertilizer has not led to consistently higher yields of crops.[16–19] Proper amounts of irrigation can minimize fertilizer losses,

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increase crop growth, and yield.[20,21] According to previous research, irrigation plants under the maximum water requirements for crops have proven suitable for conserving water. Scientists use Irrigation water calculation models like AQUACROP and CROPWAT 8.0 to determine crop evapotranspiration, crop water requirements (CWR), and irrigation scheduling.[22] The Food and Agriculture Organization (FAO) created these software programs to help irrigation engineers and agronomists perform standard calculations for water irrigation studies and manage and design irrigation schemes.[23] As a result of global climate change, the agriculture sector has begun to address water scarcity in recent years. To effectively use the limited amount of available water for agriculture, agricultural practices and understanding of water productivity must be improved[24] to increase WUE. A combination of deficit irrigation (DI) and optimized nitrogen fertilizer application to the crops can be the best possible strategy.[25] In irrigated areas, several researchers have found that deficit irrigation was a reliable strategy. [26-29]

Under deficit irrigation, coupled with bed planting, crops are deliberately permitted to some degree of irrigation shortage throughout the growing season or at specific growth stages.[30] Deficit irrigation is a water management strategy adopted to enhance Water Use Efficiency (WUE) with little effect on yield.[31] It is essential to mention that deficit irrigation may reduce crop growth and grain yield, as biomass and harvest index are reduced.[32,33] The impact of DI on the growth and productivity of various crops has been extensively studied.[34,35] DI is a successful strategy for increasing water use efficiency in many crops without causing a significant yield loss.[25,36,37] Several studies indicate that interactions between the irrigation management strategies and fertilization supply levels affect the nitrogen utilization of crops and influence the crop yield.[39,40] Therefore, it can be hypothesized that the application of deficit irrigation and defined fertilization levels can enhance the WUE and grain yield of the wheat crop when it is sown on beds.

Most farmers have small landholdings in Pakistan, i.e., < 5 ha.[41] Given the poor economic conditions of small farmers, they cannot afford costly irrigation systems such as sophisticated drip and sprinklers irrigation systems.[42] Therefore, better and affordable irrigation and soil management schemes and technologies are needed to improve WUE and fertilizer utilization. In terms of technology, farmers widely adopt the innovative wheat bed planting method in irrigated areas.[43] For management schemes, irrigation water and fertilizers need careful management to increase wheat production in irrigated regions. Ungauged flood irrigation (generally 250−300 mm) and a typical 120 kg N ha^{-1} dose are traditional farming practices for wheat sown on a flat surface in irrigated areas of Punjab province of Pakistan.[3] For small farms, these practices must be optimized for the sustainable and efficient production of the wheat crop. Therefore, it is clear that irrigation water and N fertilizer require judicious management in irrigated areas to enhance the wheat grain yield.[19]

Several studies examined the effects of FAO CROPWAT model-based irrigation levels on various crops in Pakistan.[44-48] However, the combined effect of the CROPWAT model-based irrigation levels and various nitrophos fertilizers rates on bread wheat is still unclear under bed plantation at small farms in irrigated areas of Pakistan. The main objectives of the current study were (1) to examine the coupling effects of various nitrophos fertilizer rates and CROPWAT model-based irrigation levels on the wheat grain yield, yield parameters, NUE, and WUE compared to the traditional farmers' practice; and (2) to optimize the irrigation level and nitrophos fertilizer rate for increasing the bread wheat grain yield under bed planting method. According to crop requirements, the recommended fertilizer and irrigation management practices might be used as a benchmark to develop sustainable and precision agriculture policies at small farms in irrigated areas.

Materials and methods

Experimental site

The experimental site is located at the farms of the Water Management Research Center (WMRC) (31° 38.71 N, 73° 01.27 E) at an elevation of 184 m in Faisalabad, Punjab, Pakistan. At the experimental site (Fig. 1), the mean, maximum, and minimum annual temperatures were recorded at 24 ºC, 31.6 ºC, and 17.6 ºC, respectively. However, daily maximum summer temperature reaches up to 48 ºC, and a daily minimum winter temperature touches 4.8 ºC, respectively. The summer months start from April to October, whereas the winter season spans from November to March. The average precipitation in the study area is 386 mm yr^{-1}, with the majority (60−75%) falling in the monsoon season (June to September) Figure 1. The soil is predominantly sandy loam, with low organic matter (usually decrease with increasing depth) and pH ranging from 7.0 to 8.5.[49,50] There are no salinity problems in the area. The topsoil depth of 45 cm was found to have comparatively moderate nutrient concentrations. The physiochemical soil properties of the study area are shown in Table 1.
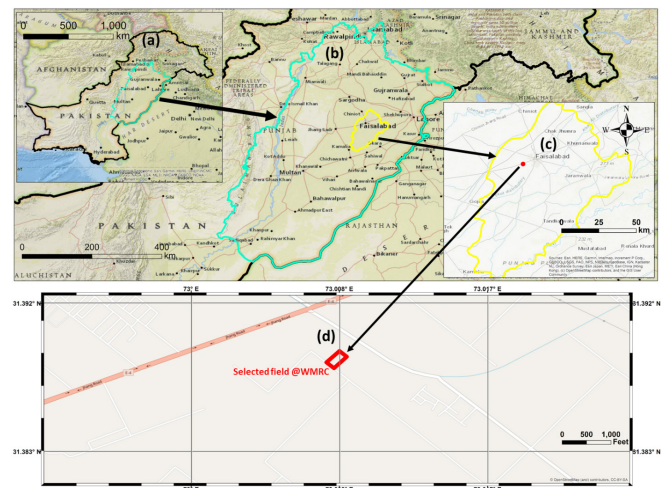

Figure 1 Location of the study area at Water Management Research Center (WMRC), Faisalabad, Punjab, Pakistan. (a) Pakistan, (b) Punjab, (c) Faisalabad, (d) selected field at WMRC.

Table 1 Soil physicochemical properties of the experimental site at WMRC Faisalabad

Properties	Depth (cm)		
	0-30	30-60	60-90
Soil texture	Sandy loam	Sandy loam	Sandy loam
Bulk density (g cm-3)	1.44	1.47	1.48
Porosity (%)	46	44	44
Field capacity (%)	23.24	21.7	21.25
Wilting point (%)	13.85	12.18	11.77
Available water (%)	9.42	9.52	9.48
EC (dS m-1)	0.38	0.35	0.38
pH	8	7.9	8
Organic matter (%)	0.56	0.35	0.31
Nitrogen (%)	0.097	0.022	0.019

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Details of experimental design and treatments

A randomized complete block design (RCBD) two-year field experimental study with three replicates was designed and executed at a trial site during the Rabi season 2014-15 and 2015-16. Basic agricultural management operations, including rotavator, planking, and ploughing, were performed for land preparation before the sowing of bread wheat. A local bread wheat variety (AAS-2011) was sown on a flat surface using the broadcasting method in traditional farming (TFP) treatment. In contrast, the seed was directly sown in optimized treatments on beds (each of 0.6 m width with four rows of wheat) using a UAF-bed planter on the 10th of November 2014 and 11th of November 2015 in the two-year field experiment. The bed-furrow geometry is shown in Figure 2. The crop was harvested with a harvester in first- and second-year experiments upon maturity on the 15th of April 2015 and 17th of April 2016.
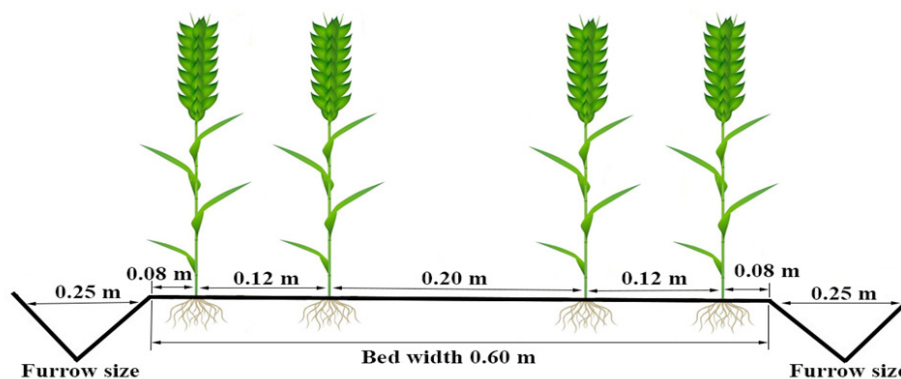

Figure 2 Bed and furrow geometry prepared by wheat bed planter under different irrigation and fertilizer treatments (T) at the experimental site.

In all the treatments, the basal dose of Muriate of Potash (MOP) 60 kg K ha^{-1} was applied as a source of potassium. Sarsabz nitrophos fertilizer (22% N and 20% P) was used as a basal dose by 40% in all treatments, and the remaining 60% applied as a top-dressing fertilizer in both year experiments. However, fertilizer in TFP treatment was used only 30% each, at the third leaf and tillering stages, the local farmer practice in the study area. According to the local area irrigation application for the wheat crop, FAO Crop irrigation model CROWAT based calculated 100% of the ETc (W100, 269 mm) was considered TFP. Optimized irrigation treatments were included 80% of the ETc (W_{80}, 215 mm) and 60% of the ETc (W_{60}, 162 mm). In each irrigation treatment, 35% were irrigated at each the third leaf and tillering stages and 30% irrigated at the shooting stage during both year experiments. Fertilizer sources were nitrophos which is acidic fertilizer having pH

3.5. The top-dressing fertilizer rate 100% TFP (N_{100}, 120 kg N ha^{-1}) was applied in two split applications, 30% each at the third leaf and tillering stages before 1st and 2nd irrigation. Optimized fertilizer treatments 80% of the TFP (N_{80}, 96 kg N ha^{-1}) and 70% of the TFP (N_{70}, 84 kg N ha^{-1}) were used in the split application 20% each at the third leaf, tillering and shooting stages, respectively before 1st, 2nd and 3rd irrigation. Irrigation water 100% of ETc and 100% of nitrogen fertilizer was considered a TFP practiced by farmers in the broadcasting method of wheat sowing in the experiments. TFP was based on the local average rate of N fertilization (120 kg N ha^{-1}) and irrigation water application (270-350 mm per wheat season). TFP (control treatment) was designed for comparison with other optimized treatments in the two-year field experiment. Treatment combinations of the amount of irrigation and fertilizer are shown in Table 2.

Table 2 Treatment combinations of Irrigation amount and nitrophos fertilization rate. The letters 'W' and 'N' represent irrigation water and fertilizer levels, respectively

Treatments	W×N	Irrigation		Fertilizer	
		ETc %	mm	%	kg N ha^{-1}
T1 (control)	$W_{100}N_{100}$	100	269	100	120
T2	$W_{100}N_{80}$	100	269	80	96
T3	$W_{100}N_{70}$	100	269	70	84
T4	$W_{80}N_{100}$	80	215	100	120
T5	$W_{80}N_{80}$	80	215	80	96
T6	$W_{80}N_{70}$	80	215	70	84
T7	$W_{60}N_{100}$	60	162	100	120
T8	$W_{60}N_{80}$	60	162	80	96
T9	$W_{60}N_{70}$	60	162	70	84

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FAO CROPWAT 8.0 model description

CROPWAT 8.0 is an FAO-developed decision-support computer program that uses rainfall, soil, crop, and environment data to measure reference evapotranspiration (ET_0), crop water requirement, irrigation scheduling, and irrigation water requirement.[51] The software helps improve irrigation schedules and the simulation of crop water use for different crops under irrigated and rainfed conditions by providing general data for various crop features, local climate, and soil properties. It is based on FAO Irrigation and Drainage Paper 56.[52]

Data requirements for CROPWAT

Rainfall, climatic, soil, and crop data are required for the CROPWAT program.[53] Rooting depth, crop coefficient, critical depletion, yield response factor, and duration of plant growth stages were all obtained from the experimental site during both years of the study and entered the CROPWAT software.[22,23] Planting dates were determined based on wheat sowing dates in both seasons. The CROPWAT model provided soil parameters such as initial water depletion, maximum rainfall penetration rate, total water availability, and maximum rooting depth. Experimental Station's soil parameters for sandy loam soil were determined by the CROPWAT 8.0 model, including total available moisture content, initial moisture depletion, maximum rooting depth, and rainfall infiltration rate. In this analysis, the United States Department of Agriculture (USDA) soil conservation approach was used.[22]

Reference evapotranspiration (ET_0)

The FAO Penman-Monteith equation (commonly known as the Penman-Monteith equation) is used in the CROPWAT model for ET_0 estimation. Most of the data was measured from the climatic data.

$$ET_o = \frac{0.408\Delta(Rn-G)+\gamma\dfrac{900}{T+273}u2(es-ea)}{\Delta+\gamma(1+0.34u2)} \qquad (1)$$

Where ET_0 is the reference evapotranspiration (mm/day), Rn is the net radiation, G is the soil heat flux, γ is psychometric constant, T is the mean daily air temperature (°C) at 2 m height, u2 is the wind speed at 2 m height (ms^{-1}), es and ea are the saturation and actual vapor pressure (kPa), respectively, and Δ is the slope of the relationship between saturation vapor pressure and air temperature.

Crop water requirement (CWR) or evapotranspiration of the crop (ET_C)

The crop water requirement is the quantity of water equivalent to what is lost from a cropped field by the ET and is represented by the rate of ET in mm/day. CWR is determined using crop evapotranspiration (ETc), which can be calculated using the equation below:[54]

$$ETc = Kc \times ET_o \qquad (2)$$

where Kc represents the crop coefficient, and it is the ratio of the crop ETc to the ET_0.

Data collection and measurement

Last ten years (2003-13), meteorological data on maximum temperature, minimum temperature, average temperature, solar radiation, reference ET, precipitation for CROPWAT 8.0 model were collected from the repository of the weather monitoring station located near the experimental area (Figure 3). CROPWAT model estimated reference ET and solar radiation according to provided climatic data. ETc was calculated according to the last ten-year climatic data (2003-2013), shown in Figure 4. Daily climatic data during the two-year experiments were regularly monitored from sowing to the harvest of the wheat crop, as shown in Figure 5.

For irrigation applications in bed furrow and flat sowing, the total water depth of each flooding was measured for the wheat crop. During every irrigation, the discharge was measured using a cutthroat flume (20 cm × 92 cm in size),[55] and the irrigation time was recorded using a stopwatch for each treatment. The amount of irrigation water was then determined from the time and discharge for the irrigation.[56] The water depth was derived from the discharge, time, and irrigated area.[57] The content of soil moisture was determined using the gravimetric method.[58] Soil samples (3 samples per plot) were collected from soil depths of 0-30, 30-60 and 60-90 cm before and after each irrigation.
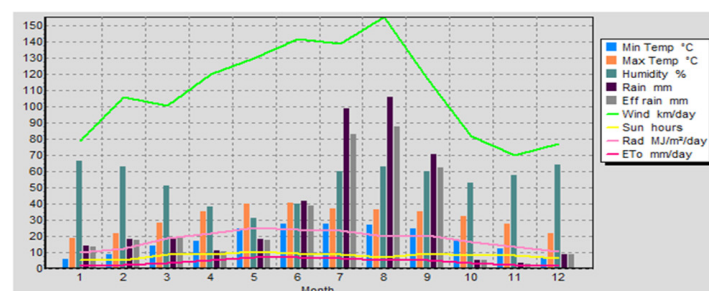

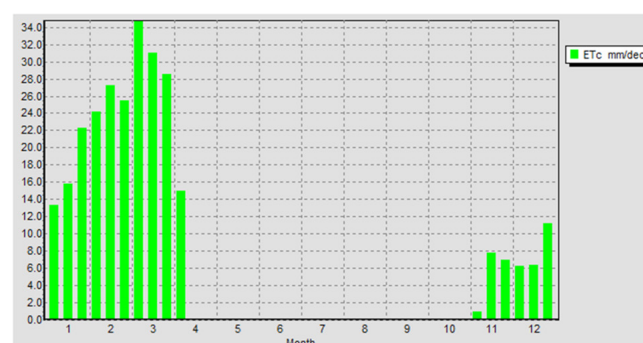**Figure 3** Average climatic data of study area from 2003 to 2013.

Figure 4 ETc of the wheat crop calculated by CROPWAT 8.0 from the mean climatic data of 2003-2013 of the experimental site.

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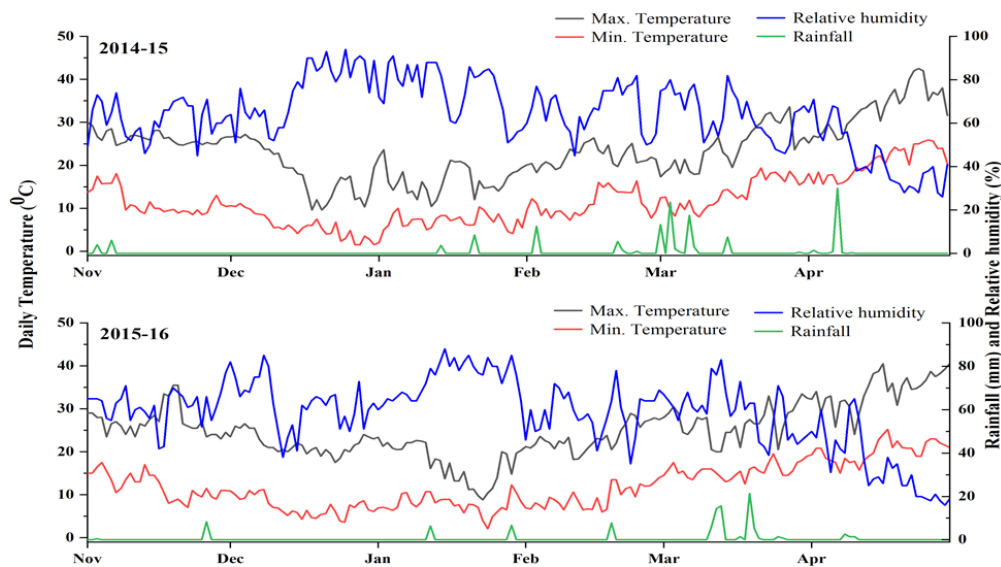©2021 Shoukat et al.   **256**

Figure 5 Daily weather data of 2014-15 and 2015-16 of experimental site monitored from sowing to harvest.

Twelve plant samples from each plot were chosen to determine plant height and yield components, such as the number of grains per spike, LAI, and spike length at the harvest. Grain yield (kg ha^{-1}), aboveground biomass (kg ha^{-1}) and 1000 grain weight (g) were calculated by taking the plant samples from 1 m^{-2} area at twelve different locations in each plot. Every experimental plot's grain yield was calculated by weighing grains after being naturally dried to a moisture content of 12 percent. The following equation was used to calculate the harvest index (HI):

$$HI\left(\%\right) = \frac{Grain\ yield}{Aboveground\ biomass} \times 100 \qquad (3)$$

where grain yield and aboveground biomass are in kg ha^{-1}.

WUE and NUE measurement:

The following relationship was used to calculate WUE (kg ha^{-1} mm^{-1}):[59]

$$WUE = \frac{Y}{ETc} \qquad (4)$$

where Y is grain yield (kg ha^{-1}) at maturity. ETc (mm) is the total seasonal evapotranspiration during a period of wheat growth.[60]

The following formula was used to calculate NUE (kg kg^{-1}) as described by Dobermann[61] and:[62]

$$NUE\ \frac{Y}{F} = \qquad (5)$$

where Y represents the wheat grain yield and F is the amount of fertilizer applied.

Data analysis

The collected data were analyzed by two-way analysis of variance (ANOVA) method using SPSS v26.0 software (IBM Corp., Chicago, IL, USA) to explore the meaning of irrigation and fertilizer treatment and their interaction effects on wheat grain yield and yield parameters as well as on WUE. The data were compared by using the Least Significance Difference (LSD) test at *P < 0.05*.

The combined ranking of different treatments and their inter-correlations based on better outputs were derived using the Principal Component Analysis (PCA) by using Minitab software (Version 19.0, Minitab Inc., Enterprise Drive State College, PA, USA).[63] PCA is a multivariate technique[64] used to analyze data containing several inter-correlated quantitative dependent variables. It extracts the critical information from data and represents it using orthogonal variables known as principal components. The similarity patterns and inter-correlations of optimized level treatments, wheat grain yield, yield parameters, NUE and WUE have displayed score and loading plots.[65]

Results

Effects of irrigation and nitrophos levels on yield and its components

The effects of CROPWAT ETc based irrigation and N fertilization on grain yield and yield parameters were assessed at different water and fertilizer input levels in a two-year experiment. The yield components (Figure 6) and grain yield (Figure 7) under deficit irrigation (DI) were increased by nitrogen application. However, maximum results were obtained with the $W_{80}N_{100}$ or $W_{80}N_{100}$ treatments than other treatments. Both irrigation and N fertilization significantly affected the grain yield and its components (Table 3). When assessing the N fertilization and deficit irrigation levels treatment, the decrease in irrigation and N levels below a specific limit (below 80% of ETc and 80% of traditional farmer practice N application was observed in our two-year experiment) showed a significant decrease in yield and its components.

Nitrophos fertilizer applications to wheat plants grown at 80% ETc ($W_{80}N_{80}$ treatment) allowed the plants to produce growth characteristics close to those obtained with farmer practice fertilizer application (N_{100}). There were savings of fertilizer and irrigation water compared to traditional farmer practice ($W_{100}N_{100}$). Optimum plant height, spike length, 1000 grain weight, grains per spike, grain yield, and aboveground biomass were obtained in $W_{80}N_{100}$ treatment, which has a non-significant difference at P<0.005 with $W_{80}N_{80}$ treatment. Compared to the control treatment ($W_{100}N_{100}$), TFP, in $W_{80}N_{100}$ and $W_{80}N_{80}$ treatments, 20% more grain yield was obtained in 2014-15 and

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21% in 2015-16 field experiments. The two-way analysis of variance found that irrigation and N fertilizer treatments significantly affect grain yield at P < 0.05. The interaction of irrigation and fertilizer treatments significantly affected the grain yield and their components. Taking into account the interaction impact of irrigation and nitrogen fertilization, statistically, treatment $W_{80}N_{100}$ and $W_{80}N_{80}$ showed optimal grain yield and yield components than other interaction levels during both growing seasons; both treatments have a non-significant difference at P<0.05.
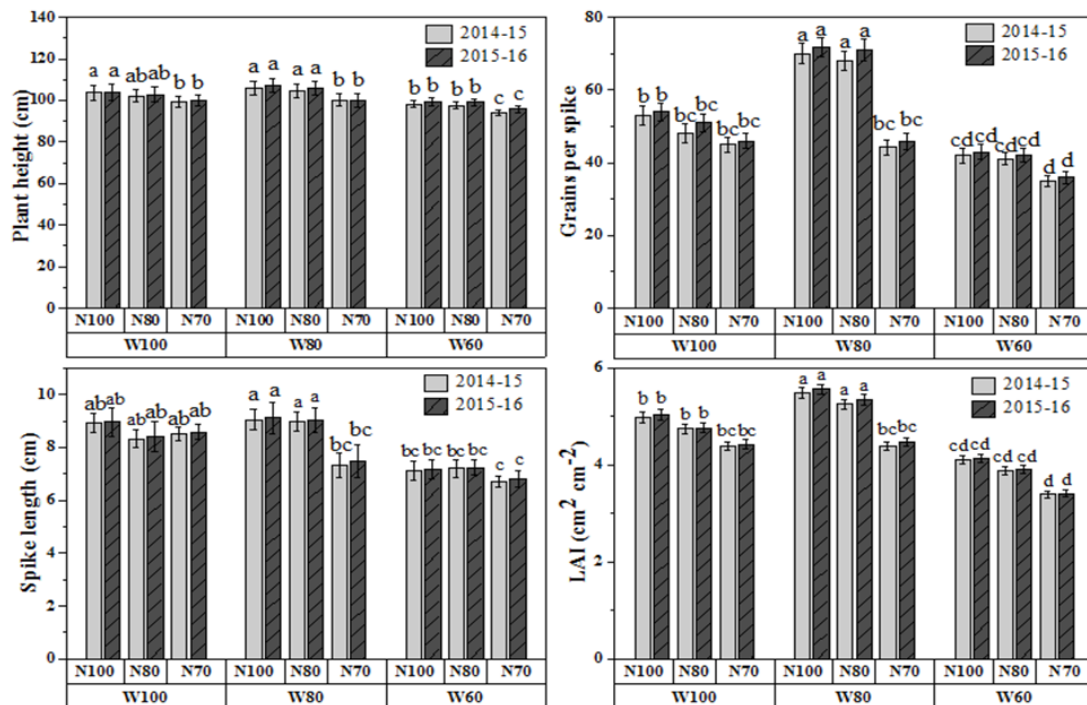

Figure 6 Effects of different levels of irrigation water and nitrophos rates on the yield-related components. Bars mean values with different letters significantly differ at the P < 0.05 level of probability between treatments. The same letter represents values that are not significantly different at the P < 0.05 level of probability according to the LSD test. Each value is the mean ± SE (n = 9).
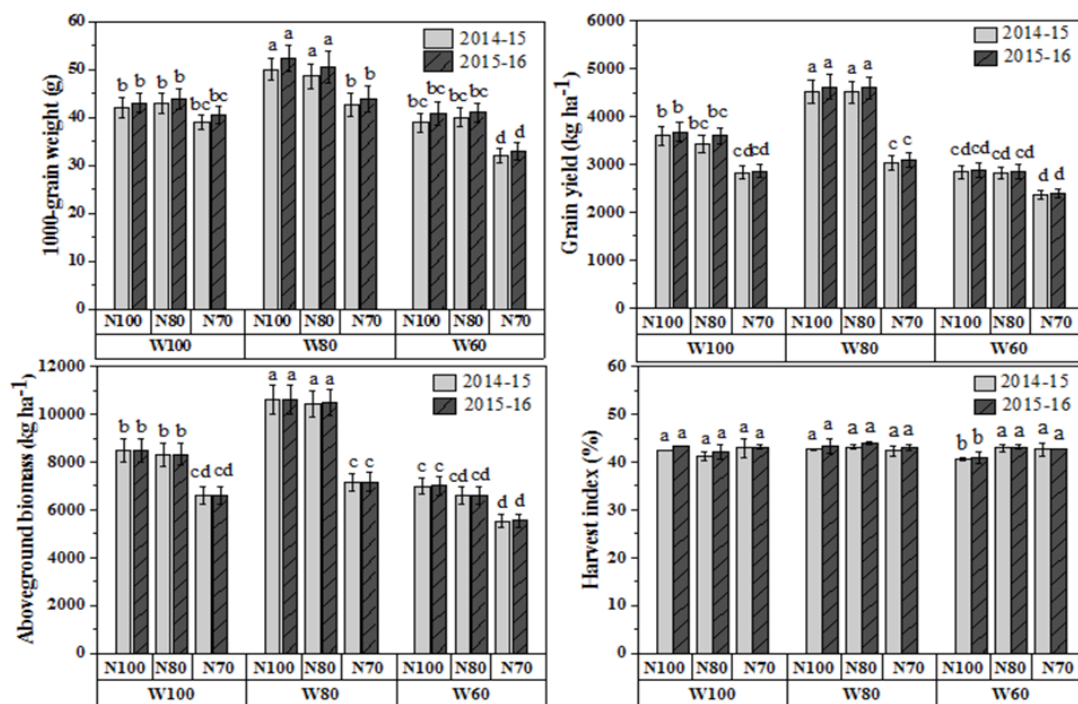

Figure 7 Effects of different levels of irrigation water and nitrogen rates on the wheat grain yield and its attributes. Bars mean values with different letters significantly differ at the P < 0.05 level of probability between treatments. The same letter represents values that are not significantly different at the P < 0.05 level of probability according to the LSD test. Each value is the mean ± SE (n=9).

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Table 3 Analysis of variance (ANOVA) of irrigation and fertilizer effects on grain yield, yield attributes, NUE, and WUE of bread wheat

Source of variation	Traits									
	PH	LAI	TGW	SL	GPS	GY	AGB	HI	NUE	WUE
W	***	***	***	***	***	***	***	***	***	***
N	***	*	***	***	**	*	ns	ns	***	ns
W×N	*	*	**	**	**	ns	ns	ns	*	ns

*Significant at P < 0.05, **Significant at P < 0.01, ***Significant at P <0.001, and ns, not significant, P ≥ 0.05. Where PH is plant height (cm), LAI is leaf area index (cm² cm⁻²), TGW is 1000 grain weight (g), SL is spike length (cm), GPS is grains per spike, GY is grain yield in (kg ha⁻¹), AGB is aboveground biomass (kg ha⁻¹), HI is harvest index (%), NUE is nutrient use efficiency (kg kg⁻¹), and WUE is water use efficiency (kg ha⁻¹ mm⁻¹)

Effects of irrigation and N levels on water and nitrogen use efficiency (WUE and NUE)

The effects of irrigation and fertilization on WUE and NUE were assessed at different water and fertilizer input levels, and it varied with varying treatments, as shown in Figure 8. ETc was measured using the FAO CROPWAT model under three different irrigation treatments I_{100}, I_{80}, and I_{60}, 269 mm, 215 mm, and 162 mm. The precipitation received during 2014-15 and 2015-16 was 133.4 mm and 102 mm. The WUE was calculated using *Eq. 4*. The WUE was found significantly higher in $W_{80}N_{100}$ and $W_{80}N_{80}$ than TFP and other treatments. It was observed that WUE reduced when the irrigation level was lower than 215 mm (80% of ETc). The WUE was 31.86% and 32.44% higher in $W_{80}N_{100}$

and $W_{80}N_{80}$ treatments than in farmer practice treatment *T1 ($W_{100}N_{100}$)* in 2014-15 and 2015-16. There was no significant difference (*P < 0.05*) in WUE under $W_{80}N_{100}$ and $W_{80}N_{80}$; however, lesser fertilizer was applied in $W_{80}N_{80}$. The lowest WUE was observed under $W_{60}N_{70}$, which could be due to inadequate irrigation and fertilizer levels. The NUE was also affected under different fertilizer and irrigation treatments, and it was calculated using *Eq. 5*. Optimal NUE with maximum yield was observed in $W_{80}N_{80}$ (36 kg kg⁻¹) compared to other treatments, and it was 36 % higher than TFP irrigation water and nitrogen application in both years of the experiment. The optimum levels of irrigation and fertilizer can significantly improve the WUE and NUE, whereas the inadequate levels could affect it negatively.
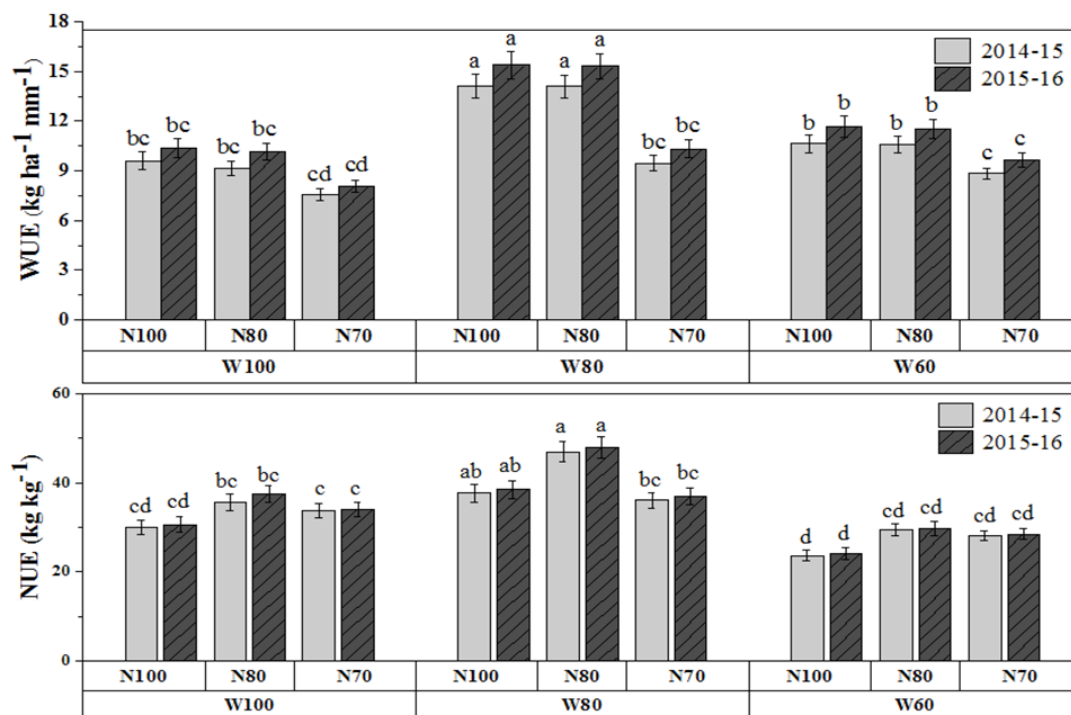

Figure 8 Effects of different levels of irrigation water and nitrophos rates on the WUE and NUE. Bars mean values with different letters significantly differ at the P<0.05 level of probability between treatments. The same letter represents values that are not significantly different at the P<0.05 level of probability according to the LSD test. Each value is the mean ± SE (n=9).

PCA approach for evaluating the various treatments effects on crop yield and its attributes

PCA showed that grain yield, yield components, NUE, and WUE positively correlated. The PCA first and second components contain the maximum variability of variability (89.3%), while only the first

component represents 79.3% variability in the observed data (Figure 5). The PCA score plot (Figure 9) showed the T4 ($W_{80}N_{100}$) and T5 ($W_{80}N_{100}$) positively correlated in the positive direction of the first component than other treatments. Most variability in the data was observed in the first component. In contrast, the T9 ($W_{60}N_{70}$) was negatively correlated in the first component of PCA. The PCA

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loading plot (Figure 10) highlighted that the optimized irrigation water and nitrogen levels of *T4* and *T5* showed positive effects on yield components, grain yield, NUE and WUE at small farms in irrigated areas. On the other hand, *T9* showed the minimum influence on the yield, yield components, NUE, and WUE. Based on the overall combined effects of optimized irrigation and fertilizer levels, the treatments were ranked as: *T5 > T4 > T1 > T2 > T6 > T3 > T8 > T7 > T9.*
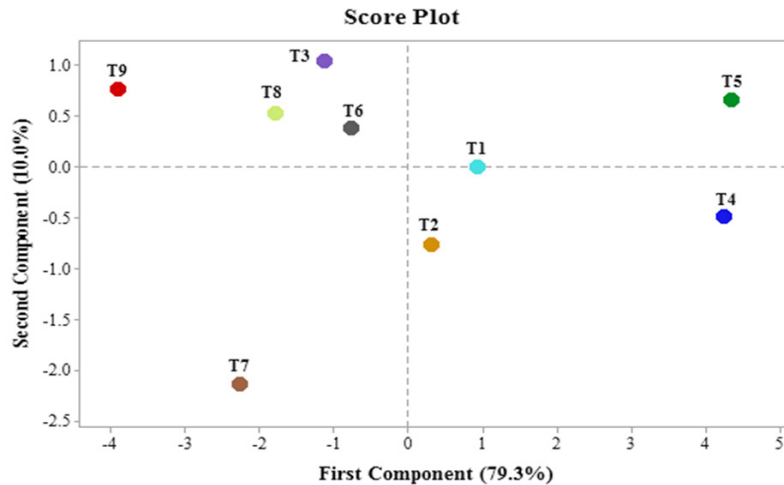

Figure 9 PCA score plot for various treatments of irrigation water and nitrogen rates.
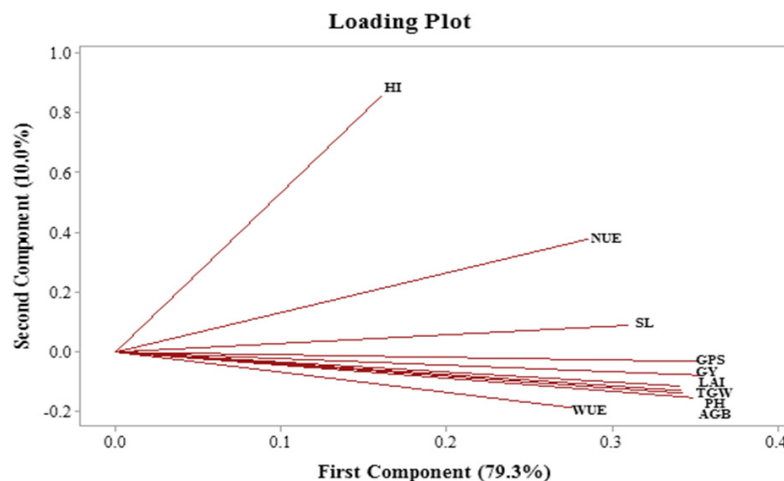

Figure 10 PCA loading plot for the effect of various treatments on grain yield, its parameters, WUE and NUE. HI indicate (harvest index), NUE (nutrient use efficiency), SL (spike length), GPS (grains per spike), GY (grain yield), LAI (leaf area index). TGW (1000-grain weight), PH (plant height), AGB (aboveground biomass) and WUE (water use efficiency).

Discussion

Two years of field research showed that optimized irrigation water and nitrophos fertilizer could increase the wheat grain yield under the bed plantation method. We examined the effects of CROPWAT ET_C-based irrigation and fertilizer levels on wheat grain yield, its parameters, NUE, and WUE under bed plantation compared to the farmer practice in flat sowing. Previous studies used the CROPWAT model to estimate crop water requirements in irrigated areas of Pakistan.[44,46,66,67] However, the coupling effects of CROPWAT ETc based deficit irrigation levels and NP fertilizer rates are unclear for bread wheat under bed planting technique in irrigated areas of Pakistan. It was hypothesized that deficit irrigation based on CROPWAT ETc and optimized fertilizer application could improve grain yield, WUE, and NUE by saving water and fertilizer. We observed that the optimal amount of water and nitrogen fertilization significantly impacted growth parameters and grain yield, which is agreed well with.[68,69]

They examined that coupling optimal moisture conditions with fertilizer level can promote root growth, allowing plants to receive more nutrients from the soil, resulting in better plant growth and development.[70] Under an open field, deficit watering with the optimal amount of fertilizer has been identified as a beneficial strategy for water[71] and fertilizer conservation at small farms in irrigated areas of Pakistan.

The maximum yield attributes (Figure 6) and wheat grain yield (Figure 7) were observed with higher nitrogen rates (100% of TFP) and 80% of the total ETc based irrigation water application estimated by the FAO CROPWAT model.[22] Statistically, there was no significant difference ($P<0.005$) was observed on grain yield and its parameters when 80 or 100% of the TFP nitrophos rates coupled with optimized irrigation (80% of total ETc) application. Our findings are in line with several other researchers,[72-77] who concluded that 80% of ETc based deficit irrigation and reduced fertilization application than farmer

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practice can substantially increase grain yield, WUE, and NUE. Irrigation and fertilizer and their interaction significantly affected the grain yield, attributes, WUE, and NUE (Table 3). Several other researchers also observed similar results.[78-80]

The irrigation water and fertilizers should be applied at the proper time and in appropriate amounts to get the higher WUE and NUE with optimal grain yield. It highlighted that applying fertilizer in the three-split application[81] rather than two split applications can be beneficial to obtain optimum grain yield.[81-84] We also found that grain yield and NUE did not always increase with enhancing the amounts of fertilizers, which is agreed well with the previous study.[85,86] Furthermore, the lower dose of nitrophos (70% of the farmer's practice in our experiment) and deficit irrigation (60% of ETc) resulted in minimum yield attributes, grain yield, WUE, and NUE. Excessive fertilizer and irrigation water application are used to enhance crop yield. However, we examined that higher fertilizer rates and irrigation application can reduce the grain yield, NUE, and WUE. An approach similar to ours has been presented before by other researchers.[87,88] Appropriate amounts of irrigation water and nitrogen fertilization rates are essential for optimal wheat development, and both have a significant impact on crop yield.

The maximum WUE (32% higher than TFP) was recorded at 80% of ETc based irrigation and full farmer practice fertilizer application (W80N100), which showed a non-significant ($P < 0.005$) difference with the W80N80 treatment (Figure 8B). Ullah[71] and[89] also observed similar effects that 80% of ETc based deficit irrigation could be the optimal application for maximum grain yield and WUE without substantial yield reduction. The maximum NUE (36% higher than TFP) was observed when 80% of CROPWAT ETc based irrigation and 80% of farmer practice nitrogen were applied compared to other treatments (Figure 8A). Irrigation dynamics usually influence the efficiency of nitrogen usage by controlling its absorption mechanisms. Nitrogen in NH_4^+ and NO_3^- is disbanded in water (present in a soil solution) and then passes from soil to roots, shoots, leaves, and other plant sections. Irrigation water, therefore, aids N plant uptake and directly correlates with N-uptake and overall NUE. Reduced NUE under less irrigation (60% of ETc in our experiment) is in line with[90] and[91] findings. They found that irrigation water application impacts the plant nitrogen uptake and its accumulation process in grains. Therefore, an adequate level of irrigation water and nitrogen is advantageous for plant water and nutrient uptake ability at the same time, leading to their most effective as also observed by.

Reducing irrigation water and nitrogen level from a specified limit can negatively impact wheat yield and parameters.[71] As a result, the various interactions of deficit irrigation and reduced nitrogen rates can be examined in the broader context in the future. PCA is a widely used method in modern data analysis and for exploring the interaction between various factors. Few researchers used it in field crop research (e.g.,[92,92] to evaluate the interaction between irrigation and fertilizer. A PCA's fundamental goal is to find patterns in data and explore correlations between variables. Our study used it to assess the relationship between treatments and various crop attributes. The results showed that the W80N100 and W80N80 treatments positively affected grain yield, yield parameters, WUE, and NUE. According to the score plot, T5 ($W_{80}N_{80}$) showed a more significant effect on crop yield than T4 ($W_{80}N_{100}$) or other treatments (Figure 9), and grain yield, yield components, WUE, and NUE are positively correlated in the loading plot (Figure 10). The optimal amount of fertilizer and irrigation level showed a substantial effect on grain yield. Several researchers have recommended applying optimized fertilizer rates[92]

and CROPWAT ETc based deficit irrigation (Li et al., 2018) for the maximum grain yield, NUE, and WUE.

Compared to two split applications of top-dressing fertilizer in TFP, three split nitrogen fertilizer applications in optimized treatments significantly improved grain yield under the bed planting technique. The findings of this study proposed that split applications of N fertilizer at three-leaf, tillering, and shooting stages before first, second and third irrigation could be an appropriate fertilization method to improve wheat growth and grain yield[95] and[95] also found that split application of top-dressing fertilizer at critical stages of the crop can improve crop growth and grain yield. It is suggested that adopting the CROPWAT ETc based optimal deficit irrigation level and optimized nitrophos fertilizer rate can be the irrigation water and fertilizer saving practice to improve wheat grain yield in irrigated areas of Punjab Pakistan. The optimal use of irrigation water and synthetic fertilizers is inevitable to maintain the maximum crop productivity in the irrigated areas.

The strength of a two-year field study was that we successfully optimized the nitrophos fertilizer rate and irrigated level for bread wheat at a small farm in the irrigated area under the bed plantation method. We used the FAO CROPWAT model to estimate various irrigation levels based on the region's climatic conditions. According to the best of our knowledge, this is the first study to examine the coupling effects of optimized CROPWAT ETc based irrigation levels and nitrophos fertilizer rates on bread wheat at small farms in an irrigated region. However, Pakistan has twelve climatic zones based on rainfall and temperature variations. There is still room for improvement in optimizing irrigation water and macro and micronutrients for bread wheat under various climatic conditions. Therefore, further field and modeling studies are needed to confirm our results under other climatic zones in Pakistan.

Conclusion

Our field study findings show that this work offers a successful crop modeling approach to maximize the bread wheat grain yield with CROPWAT ETc based on deficit irrigation level and reduced fertilizers rate. In our study, deficit irrigation level (80% of ETc) and optimal fertilizer rate (80% of farmer practice) application at the third leaf, tillering and shooting stages under bed planation produced the higher grain yield with nutrients and water use efficiencies compared to farmer practice application. Therefore, we recommended that ETc based deficit irrigation level and reduced nitrophos fertilizer rate be applied at the third leaf, tillering, and shooting stages to maximize the bread wheat grain yield under bed planting compared to the flat sowing irrigated areas of Pakistan. The FAO CROPWAT model is beneficial in estimating crop irrigation water needs and developing the irrigation deficit levels for bread wheat. The present study was limited to Pakistan's study area climatic zone; however, it is suggested it could be extended for the other climate regions further to evaluate the effect of optimal level of irrigation and fertilizer rate on bread wheat.

Authors' contributions

MRS and MS conceived the idea and designed the study. MRS conducted the fieldwork and collected the data. MRS, MS, and

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AS analyzed the data and prepared the manuscript. MRS, MS, AS, MJMC, and KM edited the manuscript.

Conflicts of interest

The authors declared no conflict of interest.

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