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Performance of Spring and Summer-Sown Maize under Different Irrigation Strategies in Pakistan

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Citation: Khan, A.G.; Imran, M.; Khan, A.-u.-H.; Fares, A.; Šimůnek, J.; Ul-Haq, T.; Alsahli, A.A.; Alyemeni, M.N.; Ali, S. Performance of Spring and Summer-Sown Maize under Different Irrigation Strategies in Pakistan. *Sustainability* **2021**, *13*, 2757. https://doi.org/10.3390/su13052757

Academic Editors: Mohammad Valipour and José Manuel Mirás-Avalos

Received: 8 December 2020
Accepted: 23 February 2021
Published: 4 March 2021

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Abstract: Pakistan is facing severe water shortages, so using the available water efficiently is essential for maximizing crop production. This can be achieved through efficient irrigation practices. Field studies were carried out to determine the dynamics of soil water and the efficiency of water utilization for maize grown under five irrigation techniques (flood-irrigated flatbed, furrow-irrigated ridge, furrow-irrigated raised bed, furrow-irrigated raised bed with plastic mulch, and sprinkler-irrigated flatbed). Spring and summer maize was grown for two years. The Irrigation Management System (IManSys) was used to estimate the irrigation requirements, evapotranspiration, and other water balance components for this study's different experimental treatments based on site-specific crop, soil, and weather parameters. The results showed that the flood irrigation flatbed (FIF) treatment produced the highest evapotranspiration, leaf area index (*LAI)*, and biomass yield compared to other treatments. However, this treatment did not produce the highest grain yield and had the lowest water use efficiency (*WUE)* and irrigation water use efficiency (WUE_i) compared to the furrow-irrigated raised-bed treatment. The furrow-irrigated raised bed with plastic mulch (FIRBM) treatment improved grain yield, *WUE*, WUE_i, and harvest index compared to the flood irrigation flatbed (FIF) treatment. The results showed a strong correlation between measured and estimated net irrigation requirements and evapotranspiration, with high r^2 values (0.93, 0.99, 0.98, and 0.98) for the spring- and summer-sown maize. It was concluded that the FIRBM treatments improved the grain yield, *WUE*, and *WUEi*, which ultimately enhanced sustainable crop production. The growing of summer-sown maize in Pakistan has the potential for sustainable maize production under the semiarid and arid climate.

Keywords: sprinkler irrigation; furrow-irrigated raised bed; irrigation management software; evapotranspiration; water use efficiency

1. Introduction

In recent decades, increasing water shortages have begun threatening food security for millions of people because more than 80% of freshwater is used by agriculture [1]. According to the International Water Management Institute (IWMI), one-third of developing countries' population lives in regions where water supplies are inadequate to meet their agricultural, domestic, and industrial needs [2]. With over 220 million people, if sufficient water supplies are not available for crop production, Pakistan cannot meet its demand for food. The per capita water supply decreased from 5600 m^3 in 1947 to only about 1000 m^3 in 2004 [3]. With the rising demand for irrigation water for agriculture, the world is now facing the challenge of producing more food with less water. Realistically, this goal can be achieved only when irrigation water utilization is more efficient. Moreover, water scarcity can be managed through optimal planning [4]. The highest (55.5 USD m^{-3}) agriculture water use efficiency in the world was reported in the Netherlands, whereas in Pakistan, it was only 0.2 USD m^{-3} [5].

Water and its movement across the soil–plant–atmosphere continuum are some of the most important core factors influencing crop productivity [6]. Efficient irrigation technologies and water management practices moderate the negative impacts of higher water use on farm incomes and environmental effects on soils and groundwater tables [7]. Many agricultural management practices have been used to increase agricultural production for many years [8]. Irrigation scheduled at different growth stages can significantly improve water use efficiency [9]. Similarly, Ref. [10] also reported that grain yield and water use efficiency (*WUE*) were strongly affected by soil water contents and irrigation scheduling. Furrow-irrigated raised-bed planting, furrow-irrigated raised bed with plastic mulch planting, and sprinkler irrigation have been proposed as three of the most significant strategies to minimize the cost of cultivation, improve *WUE*, and maximize crop yield. In bed sowing, 24% [11] and 34% [12] of water was saved compared to flat sowing. The sprinkler irrigation method has a higher potential for application efficiency than flood irrigation [13]. In the Indian subcontinent, sprinkler irrigation has increased on-farm irrigation efficiencies by up to 80% under the prevailing climatic conditions [14]. It was also found that water savings with sprinkler irrigation were 30% higher than with flatbed sowing [15]. The pivot central sprinkler irrigation practice also improved the water use efficiency, ranging from 1.07 kg m^{-3} to 2.2 kg m^{-3} [16]. There were also reports that the water use efficiency decreased when irrigation systems ignored soil variability and applied water uniformly [16].

Soil covers, such as different mulching materials, can significantly reduce evaporation and improve soil temperature and crop yield. The cost of plastic mulch is lower compared to gravel or sand, and it is easily managed. Thus, it has been widely reported that both grain yield and *WUE* can be increased under mulches [17,18]. It was observed that the soil and water conservation techniques played a significant role in decreasing water losses and increasing water infiltration [18]. It was also reported that the high moisture content was recorded in areas where conservation practices have been adapted compared to other areas where farmers ignore these practices. It was also reported that soil and water conservation practices improved soil health by increasing soil organic matter, ultimately improving water conservation [19]. These practices also improved the crop yield.

To forecast environmental parameters of interest [20], simulation models usually integrate theoretical principles, scientific information, computational algorithms, and statistical considerations. The Irrigation Management System (IManSys) [21,22] was used to estimate the irrigation requirements for this study's different experimental treatments based on site-specific crop, soil, and weather parameters.

Maize is the third most important cereal crop in Pakistan after wheat and rice, and its production increased by 6% during 2019–2020. Its contribution in value addition of agriculture is 2.9%, and it contributes 0.6% to the gross domestic production (GDP) of Pakistan. The increase in production was mainly due to the increase in cultivated area, which increases the water demand in the agriculture sector [23]. Thus, it is vital to improve the water use efficiency of maize in order to reduce agriculture's water requirement.

This study has two objectives. The first objective is to evaluate the effects of different irrigation techniques and growing seasons (spring and summer) on water use efficiency, crop yield, evapotranspiration, and soil water dynamics within and below the root zone in

Pakistan. The second objective is to evaluate the performance of IMaySys in estimating the irrigation requirements, evapotranspiration, and the rest of the water budget components of this study using site-specific weather conditions of Pakistan.

2. Materials and Methods

2.1. Experimental Site and Setup

The field experiment was conducted at the experimental farm of the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan (latitude, 31°26′ N and 73°06′ E, 184 m ASL) during the spring and summer growing seasons of 2011 and 2012. The study area's climate is semi-subtropical, arid, with more than 70% of the annual rainfall occurring from June to September. An automated weather station was installed about 500 m away from the experimental field. Reference evapotranspiration (ET_0) was calculated using the Penman–Monteith equation from meteorological variables (Figure 1).

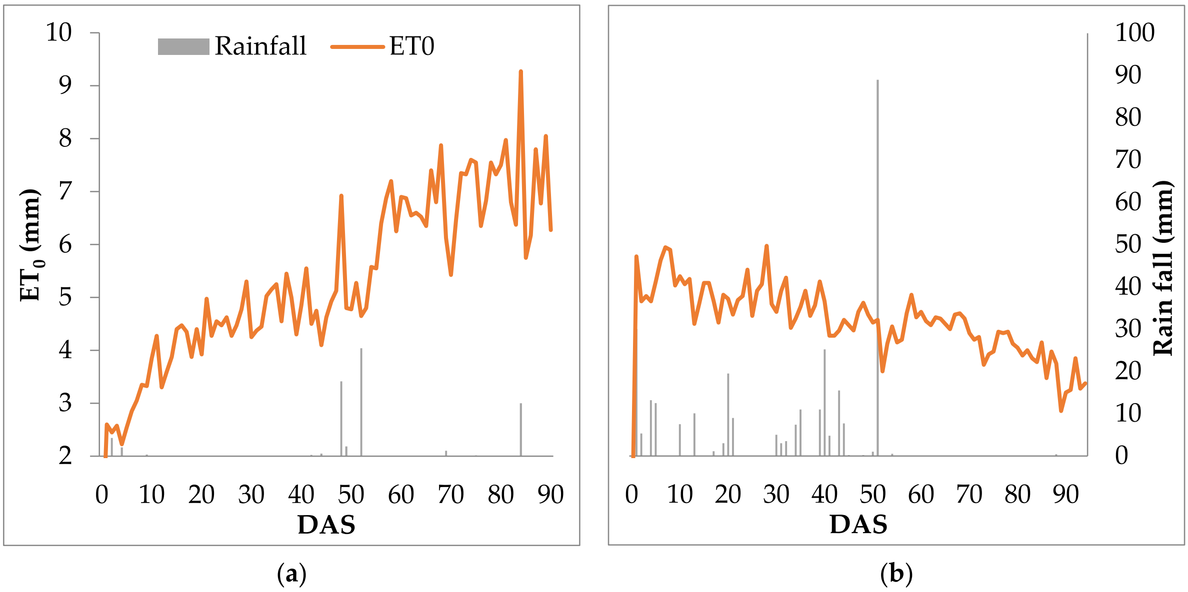


Figure 1. Daily reference evapotranspiration (ET_0) and rainfall during the (**a**) spring (average of 25 February to 29 May, 2011 and 2012) (**b**) summer (27 July to 7 November, 2011 and 2012) seasons. DAS stands for days after sowing.

The experimental site's soil type is well-drained Hafizabad loam, mixed, semiactive, isohyperthermic Typic Calciargids (Table 1). The three composite soil samples were collected from each soil layer and then analyzed for soil texture [24], soil organic matter [25], and water retention curves [26]. The soil bulk density was also determined using the core method [27] for each major soil layer at three randomly selected locations. At the same time, the saturated hydraulic conductivity (K_{fs}) was also measured at three randomly selected sites using the Guelph permeameter method (Model 2800 KI) [27].

Table 1. Measured soil physical and hydraulic parameters of the four main horizons at the experimental site.

Depth (cm)	Particle Fractions (%)			B.D.	θ_s	θ_{FC}	θ_{PWP}	θ_{AWC}	K_{fs}	SOC
	Sand	Silt	Clay	(Mg m^{-3})		—cm^3 cm^{-3}—			cm Day^{-1}	(%)
0–20	40.07 ± 0.12	37.41 ± 0.13	22.52 ± 0.10	1.45 ± 0.10	0.44 ± 0.03	0.29 ± 0.01	0.13 ± 0.01	0.16 ± 0.01	28.31 ± 1.55	0.50 ± 0.37
20–40	43.47 ± 0.15	34.08 ± 0.12	22.45 ± 0.14	1.48 ± 0.03	0.44 ± 0.02	0.27 ± 0.01	0.12 ± 0.01	0.15 ± 0.01	27.27 ± 3.01	0.34 ± 0.45
40–60	45.24 ± 0.22	32.30 ± 0.23	22.46 ± 0.12	1.55 ± 0.02	0.43 ± 0.02	0.27 ± 0.01	0.12 ± 0.01	0.15 ± 0.01	19.52 ± 4.25	0.28 ± 0.18
60–100	46.38 ± 0.19	31.21 ± 0.14	22.41 ± 0.14	1.59 ± 0.02	0.42 ± 0.01	0.27 ± 0.013	0.12 ± 0.01	0.15 ± 0.01	20.00 ± 2.35	0.22 ± 0.28

B.D = soil bulk density, θ_s = saturated water content, θ_{FC} = water content at field capacity, θ_{PWP} = water content at the permanent wilting point, θ_{AWC} = available water content, K_{fs} = field-saturated hydraulic conductivity, SOC = soil organic carbon, n = 3.

2.2. Experimental Treatments

The experimental design was a randomized complete block design with four replications, with irrigation techniques as the main treatments. Plot sizes were 4 m^2 each, separated by a 1 m crop-free buffer strip. The local high-yielding maize hybrid (DK 919) was planted. The spring sowing time was on 27 February, 2011, and 25 February, 2012. However, the summer sowing was on 27 July, 2011, and 29 July, 2012. The seeding rate was 25 kg ha^{-1}, with a 65 cm row spacing and a 22.5 cm plant to plant distance. Fields were irrigated uniformly (101.6 mm) before sowing to ensure optimum germination. Urea was applied at a rate of 250 kg N ha^{-1} in two splits. Phosphorous and potassium were applied at sowing at 150 kg ha^{-1} of single super phosphate and 105 kg ha^{-1} of potassium sulfate. The spring-sown maize was harvested on 29 May, 2011, and 27 May, 2012, whereas the summer-sown maize was harvested on 5 November, 2011, and 7 November, 2012.

The individual experimental treatments consisted of five different irrigation techniques (i.e., flood-irrigated flatbed (FIF), furrow-irrigated ridge (FIR), furrow-irrigated raised bed (FIRB), furrow-irrigated raised bed with plastic mulch (FIRBM), and sprinkler-irrigated flat sowing (SIF)). Readily available water (*RAW*) was maintained at adequate levels in all irrigation techniques so that there were no water stresses in either growing season.

2.3. Plant Measurements

From a harvested area of 1 m^2 at the center of each plot, the total aboveground biomass and grain yield were recorded. The ratio of grain yield to total biomass was calculated as the harvest index. A digital leaf area meter (YMG-A/YMG-B) was used to calculate the leaf area (*LA*) from the three randomly selected leaves (top, middle, and bottom leaves) from three randomly selected plants per replication per treatment. After the *LA* meter calibration, the Leaf Area Index (*LAI*) was calculated by dividing the total leaf area by the land area. However, in the absence of the leaf area meter, *LA* was calculated using the following formula [28]:

$$\text{Leaf area} = L \times W \times A \quad (1)$$

where L is the leaf length (m), W (m) is the greatest leaf width, and A is a factor, which has a value of 0.75 for maize. Leaf area index was measured 7, 15, 30, 60, 75, and 90 days after sowing (DAS) and at harvest.

2.4. Soil Water Content and Actual Evapotranspiration

Based on weekly measured water content readings, the amount of irrigation water needed to sustain the soil water status at *RAW* (mm) was determined and applied when required. Readily available water *(RAW)* was determined according to the formula below:

$$RAW = pTAW \tag{2}$$

where the "threshold value for readily available water" *(TAW)* for maize (p = 0.55) was taken from the FAO Irrigation and Drainage Paper No. 33 and adjusted using the following formula [29]:

$$p_{adj} = 0.55 + 0.04(5 - ET_c) \tag{3}$$

where p_{adj} is the adjusted fraction of the total available water depleted from the root zone before any moisture stress, and ET_c is the crop evapotranspiration in mm/day.

The soil water content in the top 100 cm of the soil profile was measured weekly using the Time Domain Reflectometry (Triaxial Cables Manufacturer MODEL 6050X3) form at the following soil profile sections: 0–20, 20–40, 40–60, 60–100 cm depth. The soil water content monitoring sensor was calibrated before starting the experiment using gravimetric reference samples from the corresponding depths [30]. Water contents at field capacity and a permanent wilting point (Table 1) were determined for each depth with a pressure plate apparatus at pressures of −33 and −1500 kPa, respectively [30]. Based on soil water measurements, actual evapotranspiration was calculated using the water balance equation:

$$ET_a = (I + P) - \Delta S \tag{4}$$

where ET_a is actual evapotranspiration (mm), I (mm) is irrigation, P (mm) is rainfall, and ΔS (mm) is the change in the root zone water storage. Drainage was assumed to be negligible because irrigation amounts were adequately delivered to replace depleted water based on measured soil water contents in the root zone and the optimum water-holding capacity of the soil.

2.5. Water Use Efficiency and Irrigation Water Use Efficiency

The water use efficiency (*WUE*) is defined as follows [31]:

$$WUE = \frac{GY}{ET_a} \tag{5}$$

where *WUE* (kg ha^{-1} mm^{-1}) is the water use efficiency for grain yield (kg ha^{-1}), *GY* is the grain yield (kg ha^{-1}), and ET_a (mm) is the actual evapotranspiration.

Irrigation water use efficiency (WUE_i) is calculated as follows:

$$WUE_i = \frac{GY}{I} \tag{6}$$

where I (mm) is the applied irrigation depth.

2.6. IManSys Model Simulation

The Irrigation Management System (IManSys) software was used to calculate irrigation requirements for maize, based on the site-specific data [32]. IManSys solves the following water balance equation:

$$STO = RAIN + NIR - DRAIN - RUNOFF - CANOPY\ INTERCEPTION - ET_a \tag{7}$$

where *STO* is the change in the soil water storage (mm), *RAIN* is rainfall (mm), *NIR* is the net irrigation requirement (mm), *DRAIN* is the drainage below the root zone (mm), *RUNOFF* is surface runoff (mm), the *CANOPY INTERCEPTION* is the rainfall interception by the crop (mm), and ET_a is the actual evapotranspiration (mm).

Equation (7) is rearranged, and then the gross irrigation requirements are calculated as follows:

$$NIR = (STO - NET\ RAIN + DRAIN + ET_a)/f \quad (8)$$

where f is the irrigation system efficiency accounting for irrigation losses ($f < 1$). The input data for IManSys are meteorological data (rainfall, maximum and minimum air temperatures, wind speed, and solar radiation), crop data (the initial and maximum crop root zone depths, and the initial, mid-season, and end-season crop coefficients), and the soil water-holding capacity for each soil layer. The output data include net irrigation requirement (*NIR*), effective rainfall, potential evapotranspiration (ET_0), actual evapotranspiration (ET_a), and runoff. More details about IManSys can be found in [32]. The model uses the measured gross rainfall to determine net rainfall/effective rainfall based on the crop's *LAI* and plant height.

2.7. Model Performance

IManSys model was calibrated for the net irrigation requirement (NIR) and ET_a using a data set of the 1st year of all treatments for both seasons. Soil physical and hydraulic parameters (Table 1), climatic data, rooting depth of crop, and LAI were used for calibration to achieve a goodness of fit between predicted and observed values of the water balance component. The model was then validated with the data of the second year of all treatments for both seasons. Model efficiency was calculated using the Nash and Sutcliffe method [33]:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - O)^2} \quad (9)$$

Here an *EF* value of 1 indicates that the model predicted and observed values are an exact match, and an *EF* value of 0 indicates that the mean of observed data would be a similarly accurate prediction of observed data as the model predicted values. *EF* value from $-\infty$ to 0 occurred when observed means were a better predictor than the model.

2.8. Statistical Analysis

The collected data were subjected to normality and homogeneity tests and statistically analyzed using the analysis of variance (ANOVA) techniques according to the randomized complete block design (RCBD) for both field trials. The mean values were compared using the LSD (a least-significant difference) test at $p \leq 0.05$ [34]. The software package STATISTIX 8.1 [35] was used for the statistical analysis.

3. Results and Discussion

3.1. Soil Water Dynamics

The water content in the top 20 cm (0–20 cm) showed clear differences between different treatments (Figures 2 and 3) in both growing seasons. In contrast, the water contents in lower layers showed insignificant variations due to more upward movement and negligible drainage. The water content in the upper 20 cm soil layer was highest in the FIRBM treatment than the other treatments during both growing seasons. The extent of measured water contents was as follows: FIRBM > FIRB > FIR > FIF > SIF. Both evaporation and transpiration affected the upper 20 cm soil layer. A high proportion of root water absorption normally occurs in the near-surface layers due to higher root densities near the plant base [36]. Earlier researchers reported that the plastic mulch conserved more water than other mulch materials [37]. Similarly, the highest soil water storage and low evaporation were recorded for the plastic mulch with furrow irrigation [38].

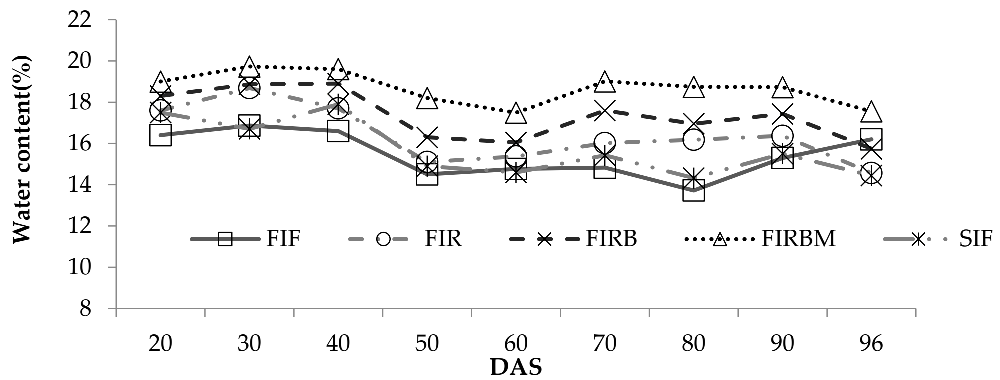


Figure 2. Measured soil water contents in the top 20 cm soil layer during the spring season.

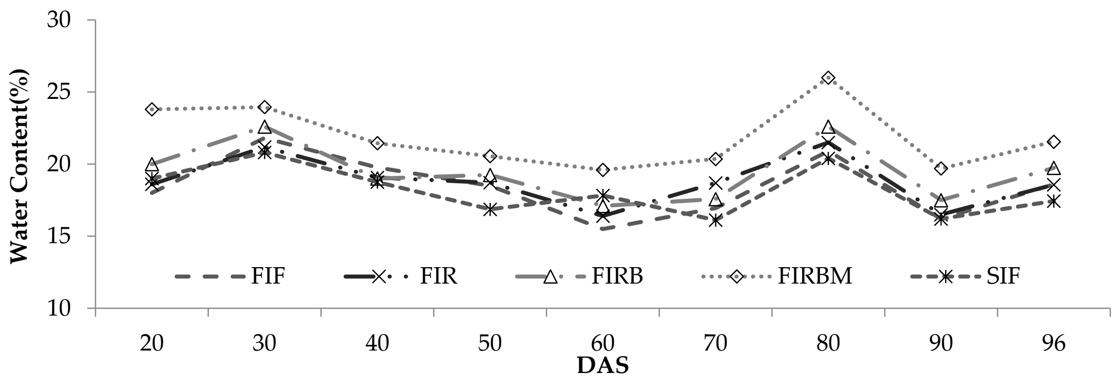


Figure 3. Measured soil water contents in the top 20 cm soil layer during the summer season.

3.2. Seasonal Water Balance among Different Irrigation Practices

The highest (420–410.5 mm) and lowest (340–290.5 mm) *NIR* amounts were recorded for the FIF and SIF treatments during the spring and summer growing seasons (Table 2). The highest seasonal evapotranspiration (475–407.5 mm) was recorded for the FIF treatment, whereas the lowest seasonal evapotranspiration (390.2–280 mm) was recorded for the SIF treatment during the spring and summer growing seasons (Table 2). There is a reasonable correlation between seasonal water evapotranspiration and the amount of net irrigation requirement (*NIR*) (Figure 4). However, the ET_a of the spring season was slightly higher than that of the summer season across all treatments. This might be attributed to differences in climatic conditions, changes in soil water storage, and a total growing season irrigation depth.

Table 2. Comparison of measured and simulated water balance components *NIR* (net amount of irrigation (irrigation (*I*) + rainfall (*RF*))), ET_a (actual evapotranspiration), and ΔS (change in soil water storage within the root zone) during the spring and summer seasons.

Treatments	Spring						Summer					
	Measured (mm)			Estimated (mm)			Measured (mm)			Estimated (mm)		
	NIR	ET_a	ΔS	*NIR*	ET_a	ΔS	*NIR*	ET_a	ΔS	*NIR*	ET_a	ΔS
* FIF	420 a [+]	475 a	−55 d	428 a	480 a	−52 c	410.5 a	407.5 a	3.0 d	415 a	412.3 a	2.7 d
FIR	410 b	457.5 b	−47.5 c	414.5 b	460 b	−55.5 d	385.5 b	374.2 b	11.3 c	395.5 b	386.4 b	9.1 b
FIRB	390.8 c	437.8 c	−47.0 bc	395.5 c	442 c	−46.5 bc	345.5 c	332.7 c	12.8 b	350.3 c	340 c	10.3 a
FIRBM	370.8 d	405.3 d	−34.5 a	372 d	410 d	−38 a	327.5 d	311.2 d	16.3 a	325 d	315 d	10.0 a
SIF	340 d	390.2 e	−50.2 b	347.5 d	392 e	−44.5 b	290.5 e	280 e	10.5 c	300.2 e	292.2 e	8.0 c

* FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. [+] Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significance difference (LSD) test.

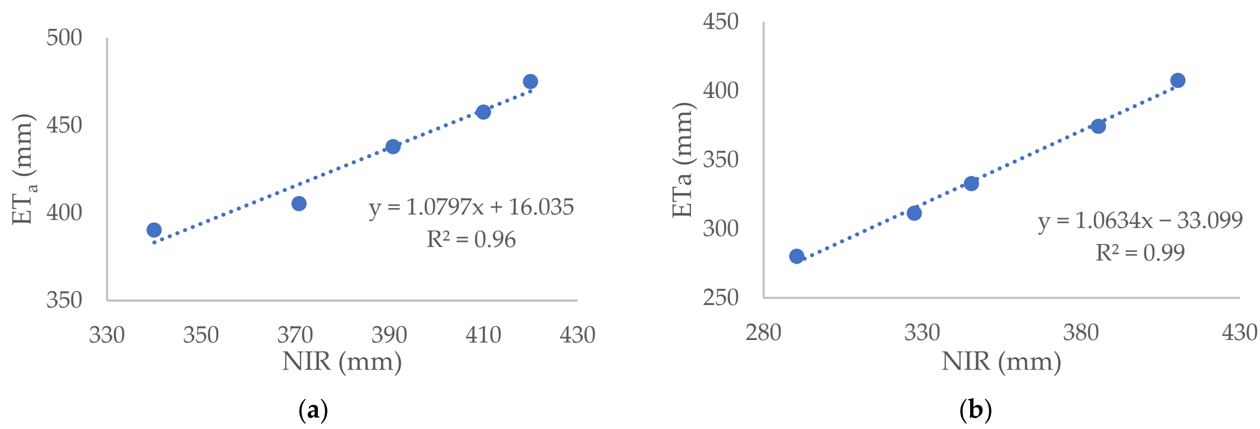


Figure 4. Correlation between ET_a and *NIR* during the (**a**) spring and (**b**) summer growing seasons.

The extent of water depletion followed the following order FIF > SIF > FIR > FIRB > FIRBM during the spring growing season. Soil water storage depletion variations across treatments impacted the crop's evapotranspiration during the growing season. Maximum soil water storage values were recorded for the furrow-irrigated raised bed with plastic mulch treatment (FIRBM) during the summer growing season. A plastic film may reduce surface water evaporation and improve soil temperatures and increase yield [39,40]. Additionally, its cost is lower than that of gravel and sand, and its operation is more straightforward. Consequently, the plastic-mulching technique is widely adopted.

3.3. Crop Growth and Yield

Crop growth and yield varied among different irrigation treatments and growing seasons (Table 3). Grain yield was the highest in the furrow-irrigated raised bed with plastic mulch (FIRBM) treatment. An increase in grain yield by 11.5 and 8.9% for the FIRB with plastic mulch was observed over FIF during the two growing seasons. This increase was likely due to higher water use efficiencies in this treatment during the two growing seasons. This treatment reduces evaporation from the soil surface due to the minimum soil exposure to direct sunlight. An increase in yield was likely due to reduced drainage from furrows and enhanced lateral water movement. These results concur with those reported by [41]. The key contributing factors of mulch in increasing grain yield include improved soil physical and chemical properties and enhanced soil biological activity [42]. Our results agree with [43], who reported that furrow irrigation significantly increased the grain yield of maize. The raised-bed treatment saved water and increased yield in the wheat–maize rotation compared to the flood-irrigated flat field [37].

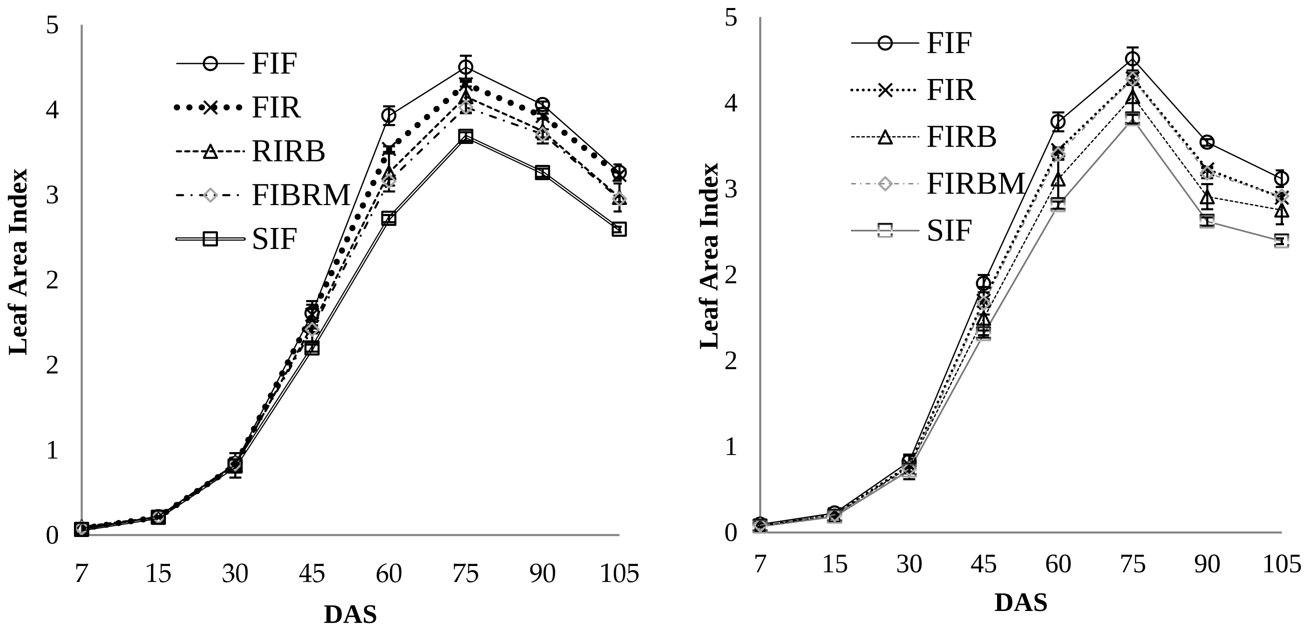
Table 3. Measured plant parameters during the spring and summer seasons.

Treatments	Spring			Summer		
	Grain Yield ($Mg\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)	Harvest Index	Grain Yield ($Mg\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)	Harvest Index
FIF	5.67 c $^{+}$	14.2 a	0.39 c	6.04 bc	16.1 a	0.37 c
FIR	6.06 abc	13.6 abc	0.44 b	6.16 bc	15.1 bc	0.40 b
FIRB	6.16 ab	13.9 ab	0.44 b	6.26 ab	15.3 ab	0.40 b
FIRBM	6.32 a	12.8 c	0.45 a	6.58 a	14.8 bc	0.44 a
SIF	5.80 bc	13.1 bc	0.44 b	5.87 c	14.3 c	0.40 b
LSD ($p \leq 0.05$)	0.48	1.10	0.01	0.37	0.91	0.01

FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. $^{+}$ Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significant difference (LSD) test.

The biomass (grain + straw) under different irrigation practices varied between 13.1 and 14.2 Mg ha^{-1} in spring and between 14.3 and 16.1 Mg ha^{-1} in summer. The higher biomass in the flood irrigation treatment (Table 3) was achieved due to higher vegetative growth as a result of higher water applications. The plant height and vegetative growth increased with higher water applications, which ultimately increased the biomass. Our results agree with [17,37], who reported that the plastic film enhanced crop yield by 21–92%. Similar to our observations, Sun et al. [39] studied the relationship between irrigation and yield and concluded that increased irrigation increased ET_c and soil evaporation and, consequently, the biomass. However, excessive irrigation was not cost effective and decreased the grain yield [41]. The highest harvest index for the FIRBM treatment was likely due to the higher total dry matter and higher grain yield in this treatment. The polythene mulch resulted in a better microenvironment and better retention of soil moisture, ultimately leading to a higher grain yield and harvest index (HI). Similar results were obtained by [42], who reported that raised-bed planting enhanced the harvest index significantly due to lessened weed infestation and lodging. The highest harvest index in the FIRBM treatment could be due to the better germination rate, higher total dry matter accumulation, and grain yield. The lowest harvest index for flood irrigation was likely due to higher plant height and biomass. These findings are validated by another researcher's observations, who also recorded the maximum HI for the raised-bed treatment [40].

The leaf area index (*LAI*) is influenced by different irrigation practices and growing seasons (Figure 5) after 45, 60, 75, and 90 days of sowing. Crop grown under the flood-irrigated flat sowing treatment during the spring season had a significantly higher leaf area index (i.e., 2.08, 3.94, 4.40, and 4.04 at 45, 60, 75, and 90 DAS, respectively). The lowest *LAI* values were obtained for the sprinkler-irrigated flatbed treatment (1.75, 2.97, 3.74, and 3.40 at 45, 60, 75, and 90 DAS, respectively). A similar trend was observed during the summer season (Figure 5b). The high *LAI* under flood irrigation may be due to the ample water availability in the root zone. These results concur with the results reported by [44].



(**a**) (**b**)

Figure 5. Leaf area index (*LAI*) during the (**a**) spring and (**b**) summer seasons (DAS—days after sowing).

3.4. Water Use Efficiency (WUE) and Irrigation Water Use Efficiency (WUE_i)

The average *WUE* varied between 11.9 and 15.2 and 14.8 and 21.1 kg ha^{-1}mm^{-1} during the spring and summer growing seasons (Table 4), respectively. The water use efficiency was highest for the FIRBM treatment and lowest for the FIF treatment during both growing seasons. However, it was statistically similar to SIF, which has an additional cost of the sprinkler system and is more expensive than plastic mulch in Pakistan. In general, *WUE* values decreased with increasing amounts of irrigation water. Reference [45] reported values of *WUE* of 5.90–7.45 kg m^{-3} from their experiments with maize in the same region of Pakistan.

Table 4. Measured water use efficiency (*WUE*) and irrigation water use efficiency (WUE_i) during the spring and summer seasons.

Treatments	Spring		Summer	
	WUE (kg ha^{-1} mm^{-1})	**WUE_i (kg ha^{-1} mm^{-1})**	**WUE (kg ha^{-1} mm^{-1})**	**WUE_i (kg ha^{-1} mm^{-1})**
FIF	11.9 d [+]	13.5 d	14.8 c	14.7 c
FIR	13.3 c	14.7 c	16.4 c	15.9 b
FIRB	14.0 b	15.7 b	18.8 b	18.1 ab
FIRBM	15.2 a	17.2 a	21.1 a	20.2 a
SIF	14.8 ab	17 ab	20.9 ab	20.0 a

FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. [+] Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significant difference (LSD) test.

Similarly, [36] reported *WUE*s of 1.96–1.99 kg grain m^{-3} for maize with the FIRB irrigation practice. One scientist also found that bed planting resulted in 34% water savings and 32 and 19% higher yields for maize and wheat crops, respectively [12]. The WUE_i in the summer season was higher in all treatments than *WUEi* in the spring season (Table 4). This could be attributed to water use from the soil water storage due to higher temperatures, higher wind speeds, and lower relative humidity levels in April and May. The maximum mean *WUEi* was observed for the FIRBM treatment (17.2 kg $ha^{-1}mm^{-1}$), while the minimum WUE_i was observed for the FIF treatment (12.1 kg $ha^{-1}mm^{-1}$) during spring. The WUE_i recorded for all treatments is ranked from high to low: FIRBM > SIF > FIRB > FIR > FIF. During the summer season, the water use efficiency was more significant than the irrigation water use efficiency due to the ample supply of water and rainfall (Table 4). The maximum mean WUE_I was observed for the FIRBM treatment (20.2 kg $ha^{-1}mm^{-1}$), and the minimum WUE_I for the FIF treatment (14.7 kg ha^{-1} mm^{-1}). Plastic mulch significantly enhanced *WUE* due to reduced evaporation water loss and an increase in transpiration. Similar results are noted by [46,47] under arid to semiarid conditions. Similarly, Reference [36] found that WUE_i generally increased with a decline in irrigation quantity.

3.5. Performance of the IManSys Model

There is a strong linear correlation between measured and estimated *ETa* for both growing seasons (Figure 6). IManSys-simulated *ETa* values fitted measured values well, with correlation coefficients of 0.99 in both spring and summer seasons. Similarly, there were also linear relationships between measured and estimated *NIR* values (Figure 7). IManSys fitted the *NIR* values well, with r^2 values of 0.99 and 0.98 in the spring and summer seasons, respectively. Strong correlations were thus obtained between measured and estimated values of both *NIR* and ET_a. Our results are in line with a previous study in which the model performed well under similar environmental conditions [22].

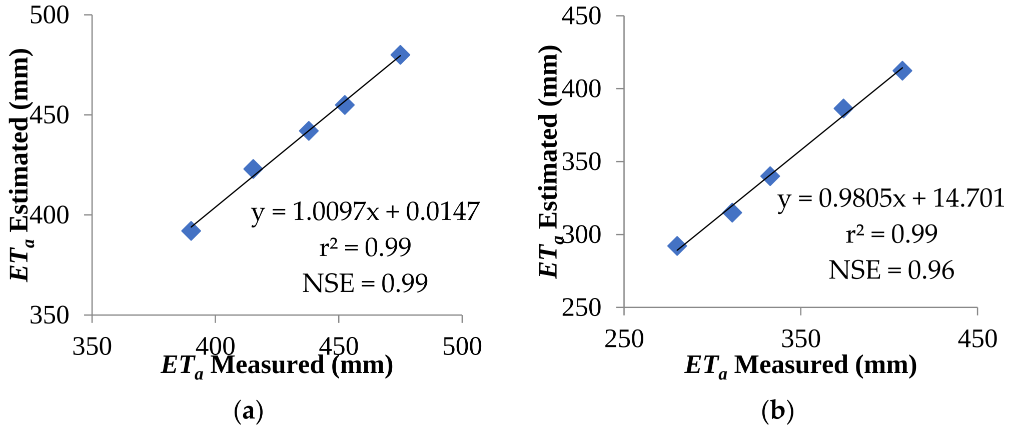


Figure 6. Correlation between measured and simulated evapotranspiration (ET_a) in the (**a**) spring and (**b**) summer seasons.

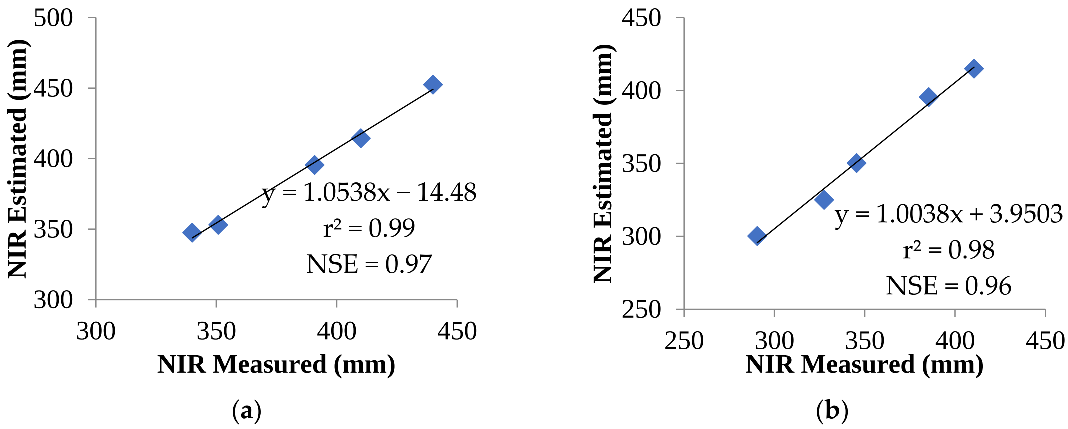


Figure 7. Correlation between measured and simulated net irrigation requirements *(NIR)* in the (**a**) spring and (**b**) summer season.

4. Conclusions

Most of Pakistan is arid to semiarid and faces water scarcity. A limited supply of irrigation water makes agricultural production in this region more expensive. Therefore, the development of water-saving agricultural practices is required to cope with water shortages during different growth stages of the maize crop in Pakistan. It was concluded from the results of this study that in Pakistan, the sowing of summer maize is more profitable compared to spring-sown maize. Experimental results also showed that different irrigation techniques have significantly affected the water use efficiency, the irrigation water use efficiency, the soil water balance, and crop yield. The best results were obtained for the furrow-irrigated raised bed covered with plastic mulch treatment. Results further showed that this treatment also produced an increase in soil water storage. Our findings further clarified that the Irrigation Management System Software could be an effective tool for irrigation scheduling for successful crop production in Pakistan's semiarid regions. We recommend to the farmers of this region to use this software for irrigation scheduling.

Author Contributions: Conceptualization, A.G.K., A.-u.-H.K., A.F., J.Š., A.A.A., M.N.A. and S.A.; Data curation, A.G.K. and M.I.; Formal analysis, A.G.K., M.I. and T.U.-H.; Funding acquisition, A.A.A. and M.N.A.; Investigation, M.I., A.F. and T.U.-H.; Methodology, A.G.K., M.I. and T.U.-H.; Project administration, J.Š.; Resources, A.-u.-H.K., J.Š., T.U.-H., A.A.A. and M.N.A.; Software, A.-u.-H.K., A.F. and S.A.; Supervision, A.-u.-H.K.; Validation, A.G.K. and M.I.; Visualization, M.I. and T.U.-H.; Writing—original draft, A.G.K., M.I., A.A.A. and S.A.; Writing—review & editing, A.-u.-H.K., A.F., J.Š., M.N.A. and S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially supported by the Higher Education Commission, Pakistan, under IRSPI Program. The authors would like to extend their sincere appreciation to the Researchers Supporting Project Number (RSP-2020/236), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was partially supported by the Higher Education Commission of Pakistan. The authors would like to extend their sincere appreciation to the University of Agriculture, Faisalabad. The authors would like to extend their sincere appreciation to the Researchers Supporting Project Number (RSP-2020/236), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest.

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