



Article Performance of Hybrid Wheat Cultivars Facing Deficit Irrigation under Semi-Arid Climate in Pakistan

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Abstract: Predicted decrease in water availability for crop production and uncertainty in climatic conditions require devising the irrigation strategies to increase water use efficiency (WUE) for sustainable crop production. The development of crop cultivars with higher WUE is a pre-requisite for such strategies, particularly in developing countries, including Pakistan, who face stern food security challenges. A two-year field study was conducted following a split-plot randomized complete block design to understand the effects of wheat cultivars (hybrid cultivars, 18A-1 and 18A-2, and local cultivar Ghaneemat IBGE-2016), sowing dates (15th November, 30th November, and 15th December), and irrigation regimes [I (103 mm), II (175 mm), III (254 mm), and IV (330 mm)] at four different growth stages of tillering, booting, anthesis and grain filling on wheat productivity, biomass production and grain yield, and crop-water relations. Early sown hybrid cultivars 18A-1 and 18A-2 showed significantly higher biological and grain yields compared to the local cultivar (59% and 69% higher than the local cultivar). Trends in biomass production and grain yield were also similar at later sowing dates of 30th November and 15th December. However, biological and grain yields decreased with delay in sowing for each cultivar. The data also revealed that hybrid cultivars were better suited to deficient irrigation and generally produced significantly higher biological and grain yields under each moisture regime. Cultivars, sowing dates, and irrigation regime differed significantly for their effects on the Soil Plant Analysis Development (SPAD) values, chlorophyll a and b contents but not for carotenoids. Sowing dates and irrigation regimes had significant effects on relative water content (RWC), water saturation deficit (WSD), water uptake capacity (WUC), and water retention capacity (WRC); however, only WUC varied significantly between the cultivars. The phenological data show that hybrid cultivars took more days to maturity and grain filling than the local cultivar, and days decreased with delayed sowing. The biological and grain yields show significant positive correlations with SPAD values (p < 0.001) and days to maturity (p < 0.001). Our study shows that hybrid wheat cultivars can be opted for higher biomass production and grain yields under deficit irrigation scenarios of semi-arid climatic conditions in Pakistan. Moreover, the hybrid wheat cultivars can perform better than the indigenous cultivar even for delayed sowing dates of 30th November and 15th December.

Keywords: hybrid wheat cultivar; irrigation regime; sowing dates; crop-water relations; grain yield



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1. Introduction

Global climate change is predicted to enhance the frequency and occurrence of dry weather conditions with concomitant adverse effects on cereal production and food security [1–3]. Fresh water availability is decreasing and has become a serious ecological factor that limits agricultural production [4]. The adverse effects of fresh water scarcity on crops coupled with the irrigation costs, restricted water resources, and insufficient irrigation facilities have compelled the farmers to use irrigation water more efficiently [5,6]. Appropriate irrigation strategies are, therefore, required to increase water use efficiency (WUE) for sustainable crop production [7]. Moreover, the fundamental approach for sustainable cereal production under semi-arid climatic conditions is to use irrigation water efficiently by developing water-saving farming strategies and improving WUE [2,8]. In cereals, adequate water availability after anthesis gives extra time to translocate carbohydrates to grains and, hence, increase photosynthetic efficiency and grain yields [9,10]. Current fresh water scarcity is threatening winter wheat productivity, and this trend is anticipated to increase many-folds in the future. Therefore, the farmers have to deal with fresh water scarcity by adopting water management techniques for sustaining winter wheat productivity and grain yield. Resultantly, deficit irrigation is considered an effective measure to increase irrigation water productivity in arid and semi-arid regions, including Pakistan [11–13].

The strategy of applying irrigation during drought-sensitive growth stages of crops is called deficit irrigation, and it has been successfully used to improve crop yields such as rice [14], corn [15], forages [16], oilseed rape [17], and soybean [18]. However, many studies have also found a substantial reduction in grain yield of several crops including winter wheat under deficit irrigation practices. The wheat yield can be optimized when the crop is subjected to deficit irrigation up to 75% of soil water deficit [19]. Water use efficiency is the ratio of dry matter production to the total amount of water applied. The improvement in biomass production per unit of water used showed an increase in WUE [20]. Furthermore, WUE is an imperative attribute to measure the drought tolerance of crops [21]. Similarly, Li et al. [22] also found a significant increase in winter wheat grain yield and WUE under deficit irrigation. Recent studies have further suggested that deficient irrigation has the potential to increase crop production by enhancing WUE in semi-arid regions [23]. Moreover, deficit and supplementary irrigation scheduling have become core strategies to deal with climatic variability [24].

Sowing time is an important agronomic factor determining the production of high yielding cereal crops because it influences the duration and timing of reproductive and vegetative growth stages [25]. Late-planted wheat grows slowly due to low temperature and results in poor germination, fewer crop stands, and low grain quality. Delay in sowing beyond recommended sowing dates reduces the number of growing days and yield of wheat because of exposure to higher temperatures at later growth stages towards maturity [26,27]. During the growth cycle, crop varieties vary in their growth and input requirements based on their genotypic characteristics and suitability to different environmental conditions. About 9.25 million ha of wheat is cultivated in Pakistan with the production of 25.5 million tons, while in the province of Khyber Pakhtunkhwa (KP), it was cultivated on about 0.75 million ha with an estimated production of about 1.4 million tons [28]. In the KP province, wheat is grown on more than 52% cultivated area as a rainfed crop with low average yields due to lack of appropriate wheat cultivars suitable for the local climatic conditions and sowing time in winter [29]. In given agro-climatic conditions, the growth and development of wheat cultivars differ, and, therefore, identification of cultivars having specific recommended sowing dates is critical for optimum crop yields. Considering the significance of appropriate variety for the rainfed/irrigated regions of Pakistan and particularly in the KP province, selection of the drought-resistant and/or -tolerant wheat cultivars is a pre-requisite for higher crop yields under deficient moisture conditions. Under such scenarios, drought-tolerant or -resistant varieties can survive better [30,31]. Hybrid crop cultivars have been widely adopted to improve crop production and yield under various environmental stresses to fit desirable agronomic conditions such

as deficit irrigation and droughts [32]. Despite earlier failures in developing hybrid wheat cultivars, they have been marketed in Europe and the USA in the 1990s, whereas efforts on hybrid wheat in China started during the late 1980s; however, work on hybrid wheat in India and Pakistan is still at an initial stage of development [33].

Despite being the eighth largest wheat growing country in the world, Pakistan is ranked at the 40th place for the average yield, and the historical data suggest that the average wheat yield has not improved much over the last two decades [34,35]. Therefore, hybrid wheat cultivars can improve wheat production by overcoming various biotic and abiotic stresses to close the yield gaps and ensure food security [36,37]. We hypothesized that hybrid wheat cultivars are a better option for higher crop yields under deficit irrigation due to better phenological traits, crop-water relationships, and higher WUE. The objectives of this pioneer two-year field study under the semi-arid climatic conditions in Pakistan were to:

- Investigate the performance of two hybrid (18A-A & 18A-2) and a local (Ghaneemat IBGE 2016) wheat cultivars grown under four deficit irrigation water regimes and sown at three dates of 15 November, 30 November, and 15 December;
- (2) Understand the relationships between phenological traits, crop-water relationships, and biological and grain yields of hybrid and local wheat cultivars.

2. Materials and Methods

2.1. Study Site Characteristics

A two-year field study was conducted at the Agronomy Research Farm, The University of Agriculture Peshawar Pakistan (34.0206° N, 71.4815° E). The site has warm–hot, semiarid, sub-tropical, and continental climatic conditions, having a mean cumulative rainfall of 360 mm and being situated at 331 m above sea level. The average winter rainfall is higher than that of the summer. From May to September in Summer, the mean maximum and minimum temperature are 40 °C and 25 °C, respectively (Figure 1), whereas from December to March in winter, the mean minimum and maximum temperature are 4.0 °C and 18.4 °C, respectively. The historical data of the last two decades suggest that the mean annual maximum and minimum temperature were 26.3 °C and 12.5 °C, respectively, whereas the mean annual rainfall was 66.2 mm in the study site region. The soil at the study site is alkaline calcareous silty clay loam with low total organic C and N contents of 8.21 g kg⁻¹ and 0.52 g kg⁻¹, respectively (Table 1). The soil is known to have low native fertility under the prevalence of semi-arid climatic conditions.



Figure 1. Average means monthly weather data of two years (2018–2019 and 2019–2020) experimental location for the crop growth season. Nov = November, Dec = December, Jan = January, Feb = February. (Source: Peshawar Metrological Department).

Properties	Values
pH (H ₂ O)	8.01
Electrical conductivity (dS m^{-1})	0.86
Bulk density (g^{-1} cm ³)	1.67
Sand (%)	8.67
Silt (%)	52.43
Clay (%)	38.90
Textural class	Silty clay loam
CaCO ₃ (%)	14.2
Total organic C (g kg $^{-1}$)	8.21
Total N (g kg $^{-1}$)	0.52
Field capacity (%)	32.81
Permanent wilting point (%)	18.41
AB-DTPA extractible nutrients	
$P (mg kg^{-1})$	3.78
K (mg kg ^{-1})	104
$Zn (mg kg^{-1})$	0.84
$Mg (mg kg^{-1})$	2.21
Na (mg kg^{-1})	2.30

Table 1. Physico-chemical properties of soil at the experimental site.

2.2. Treatments and Field Experiments

The three-factor two-year field study consisted of four irrigation regimes (I: Irrigation at tillering stage (GS 20–29), II: Irrigation at tillering stage (GS 20–29) + booting stage (GS 41–47), III: Irrigation at tillering stage (GS 20–29) + booting stage (GS 41–47) + flowering stage (GS 61–69), and IV: Irrigation at tillering stage (GS 20–29) + booting stage (GS 41–47) + flowering stage (GS 61–69) + grain filling stage (GS 70–89)), three sowing dates (SD1: 15th November, SD2: 30th November, and SD3: 15th December) and three wheat cultivars (two hybrids cultivars (18A-1 and 18A-2) and a local cultivar (Ghaneemat, IBGE 2016)). The cumulative irrigation under each irrigation regime, including the contribution from rainfall, showed some variations due to the differences in rainfall during the growth years; however, total irrigation amounts under each moisture regime were higher in the year 2019–2020 than in 2018–2019 because of higher rainfall (Table 2). On average, total irrigation provided in 2018–2019 was 95, 172, 249, and 326 mm for I, II, III, and IV irrigation regimes, respectively; and 110, 179, 259, and 334 mm for I, II, III, and IV irrigation regimes, respectively, in 2019–2020. Over the two-year period, the average total irrigation was 103, 175, 254, and 330 mm under I, II, III, and IV irrigation regimes, respectively. The contribution from the rainfall under irrigation regimes also varied with sowing dates in both years. However, despite the variations in contributions from rainfall, the average gradient between the irrigation regimes remained more or less similar, i.e., 77 and 75 mm in 2018–2019 and 2019–2020, respectively. These water regimes were strategically adopted considering the effects of water deficiency at critical growth stages of wheat as well as excessive irrigation that result in water loss from drainage. Depending on the SDs, compared to normal irrigation, the average water savings under these irrigation regimes over the two growth seasons were 29.4% and 48.3% with and without rainfall, respectively (Table S1).

Irrigation Regime	Sowing Dates	Irrigation Required (mm)	Rainfall (mm)		Irrigation Applied (mm)		Rainfall after Irrigation (mm)		Total Irrigation (mm)		Average Irrigation
5 5			2018-2019	2019–2020	2018-2019	2019–2020	2018-2019	2019–2020	2018-2019	2019–2020	(mm)
I: Irrigation at tillering stage	15 November	77	8	33	69	44	20	35	97	112	105
	30 November	77	58	8	19	69	10	23	87	100	94
	15 December	77	51	12	26	65	24	42	101	119	110
II: Irrigations at tillering and booting stages	15 November	154	8	41	146	113	20	25	174	179	177
	30 November	154	58	29	96	125	10	17	164	171	168
	15 December	154	51	51	103	103	24	32	178	186	182
III: Irrigations at tillering, booting, and flowering stages	15 November	231	8	45	223	186	20	25	251	256	254
	30 November	231	58	38	173	193	10	15	241	246	244
	15 December	231	45	76	186	155	24	45	255	276	266
IV: Irrigations at tillering, booting, flowering, and grain filling stages	15 November	308	8	33	300	275	20	20	328	328	328
	30 November	308	56	76	252	232	10	10	318	318	318
	15 December	308	45	99	263	209	24	49	332	357	345

Table 2	Brookdown	of the irrigation	n nowidad unda	r different maisture	ragimas an	d couving dates
Table 2.	Dreakdown	i of the irrigation	i provided unde	r amerent moisture	e regimes and	a sowing dates.

The field experiments were conducted following a fully factorial, split-plot, randomized, complete block experimental design with irrigation regime as main plot factor, and each treatment had three replicates. The field was ploughed two times with a cultivator, followed by pulverizing with a rotavator and leveled by using a leveler. The plot size was 12.6 m² (length 3 m, width 4.2 m), accommodating for 14 rows 30 cm apart per acre. The seeds of hybrid wheat cultivars were provided by Beijing Engineering Research Center China, whereas local wheat cultivar was obtained from the Institute of Biotechnology & Engineering, The University of Agriculture Peshawar, Pakistan. The crop was planted on three sowing dates, i.e., 15th November, 30th November, and 15th December, using the seed rate of 120 kg ha⁻¹ following a manual hand hoeing method. Nitrogen, phosphorous, and potassium fertilizers were applied at the rate of 120, 80, and 60 kg ha⁻¹ using urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively. All phosphorus and potassium fertilizers were applied at the time of sowing, while nitrogen was applied in split doses at sowing, tillering, and booting growth stages through the broadcast method. Weeds were controlled through herbicide spray Affinity [C₃H₁₄CLN₃ (6-chloro-4-N-ethyl-2-Npropan-2-yl-1,3,5-triazine-2,4-diamine)] at 30 days after sowing. Irrigations were provided to plots according to treatments and irrigation regimes using flume instrument so that a precise quaintly of irrigation was applied. Flume was placed in the irrigation channel and leveled through the leveler. The discharge was measured by allowing the canal water to flow through a converged section of flume with a depressed bottom.

2.3. Plant Measurements and Analysis

2.3.1. Phenological Traits

After the crop emergence, five plants were randomly selected from each treatment plot to record phenological traits' data, including days to tillering, jointing, heading, anthesis, and physiological maturity. Similarly, after collecting the data for physiological maturity, data for grain-filling days were also collected.

2.3.2. Crop–Water Relations

The crop–water related parameters, i.e., relative water content (RWC), water saturation deficit (WSD), water uptake capacity (WUC), and water retention capacity (WRC), were determined using the method of Henson et al. [38]. Briefly, three leaves were selected from three randomly sampled plants from each experimental plot and weighed to record fresh weight. These leaf samples were then dipped in glass beakers containing distilled water and kept for 24 h. After 24 h, the samples were taken out, and the turgor weight was recorded. The samples were placed in an oven at 65 °C for 72 h, and the dry weight was recorded. The crop–water relationship parameters were found using the following formulae:

$$WSD(\%) = [(TW - FW)/(TW - DW)] \times 100$$
 (2)

$$WUC (\%) = (TW - FW) / DW$$
(3)

WRC (%) =
$$(TW/DW) \times 100$$
 (4)

where FW is fresh weight (g), DW is dry weight (g), and TW is turgor weight (g).

2.3.3. Chlorophyll and Carotenoids Contents

The Soil Plant Analysis Development (SPAD) values of leaves were determined using a digital spade meter (SPAD 502 Plus Chlorophyll Meter, Spectrum Technologies Inc., Aurora, IL, USA). Five plants were selected at random in each treatment plot, and the SPAD values were measured with the digital spade meter from lower, middle, and upper leaves at the anthesis growth stages to reflect the leaf chlorophyll contents.

Chlorophyll a and b contents were also determined in green leaves at the anthesis stage. Mature green leaves were sampled from each plot, rinsed with distilled water, and

dried with blotting paper. For extraction of chlorophyll contents, 0.2 g leaf samples were ground with 10 mL of 80% acetone in a mortar and pestle on ice, and the suspensions were centrifuged at 4000 rpm for 10 min. The extracts were filtered through Whatman#1 filter papers by giving two 5 mL 80% acetone washings of the mixture to get a final volume of 25 mL for analysis. The absorbance of the samples was measured at 663 and 645 nm, respectively, on a UV Spectrophotometer (Dynamica Halo DB-20 Series, UK) to find the chlorophyll a and b contents [39].

The same extracts were used to find the carotenoid contents by measuring their absorbance at 480 nm, and carotenoid contents were calculated using the following equation:

Carotenoids
$$(\text{mg g}^{-1}) = \frac{1000A_{480} - 2.27C_a - 81.4C_b}{227} \times \text{V1000} \times \text{W}$$
 (5)

where A is the absorbance at specific wavelength, Ca is chlorophyll a contents, Cb is chlorophyll b contents, V is final volume of extract, and W is fresh weight of leaf tissue used.

2.4. Biological and Grain Yields

At maturity in the first week of May, six central rows from each treatment plot were harvested to record biomass production and grain yields. After harvesting, the plants were placed in the field for sun drying for three days before grains were separated from straw to weigh the grain and straw biomass to express the biological and grain yields as a ton per hectare (t ha⁻¹).

2.5. Statistical Analysis

Linear mixed model analysis was applied to find the effects of wheat cultivars (C), sowing dates (SD), and irrigation regimes (I) on phenological traits, water relationships, physiological parameters, and biological and grain yield growth and yield of wheat. Generalized linear mixed model was:

Response = Y+Y(R)+I+D+I*D+Y*I+Y*DxY*I*D+Y*R*I*D(E)+H+Y*H+I*H+D*H+I*D*H+Y*I*H+Y*D*Hx Y*I*D*H + Y*R*I*D*H (E)(6)

where Y is the year, I is irrigation, D is the sowing date, H is the hybrid, and (E) refers to the residual error.

Tukey's post hoc test was used for multiple means comparisons by splitting the data into cultivars, irrigation regimes, and sowing dates. Correlation plots were developed to find the relationship of biological and grain yields with phenological and physiological traits. Figures and tables contain mean data of six replicates from two-year experiment unless otherwise specified. Statistical analyses were performed using SPSS for Windows software v. 19.

3. Results

3.1. Effects on Phenological Traits

Wheat cultivars (C) sowing dates (SD) significantly affected days for tillering, jointing, heading, anthesis, physiological maturity, and grain filling, whereas irrigation regimes (I) showed significant effects on days for heading, anthesis, physiological maturity, and grain filling (Tables S2 and 3).

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	Days to Tillering										
Irrigation Regimes		15 November			30 November		15 December				
negimes	IBGE	18A-1	18A-2	IBGE	18A-1	18A-2	IBGE	18A-1	18A-2		
I	$45\pm2aA$	$43\pm1aA$	$47\pm2~aA$	$42\pm1~aA$	$44\pm1~\mathrm{aA}$	$46\pm1~\mathrm{aA}$	$35\pm1~\mathrm{aA}$	$41\pm5~\mathrm{aA}$	$39\pm1~\mathrm{aA}$		
Π	$46\pm3aA$	$45\pm2~aA$	$49\pm 6~aA$	$44\pm1\mathrm{aA}$	$44\pm1~\mathrm{aA}$	$46\pm1\mathrm{aA}$	$35\pm1~\mathrm{aA}$	$36\pm1\mathrm{aA}$	$39\pm1bA$		
III	$43\pm1~\mathrm{aA}$	$45\pm1\mathrm{aA}$	$47\pm2~aA$	$43\pm1aA$	$45\pm1~\mathrm{abA}$	$48\pm1\mathrm{bA}$	$35\pm1aA$	$37\pm1~abA$	$39\pm1bA$		
IV	$44\pm2aA$	$44\pm1\mathrm{aA}$	$48\pm1~\mathrm{aA}$	$42\pm1~aA$	$43\pm1~\text{aA}$	$46\pm1~\mathrm{aA}$	$35\pm1~aA$	$38\pm1bA$	$39\pm1bA$		
	Days to jointing										
I	$64\pm1\mathrm{aA}$	$67 \pm 1 \text{ aA}$	$71\pm2bA$	$61 \pm 1 \text{ aA}$	$64\pm1~\mathrm{aA}$	$67 \pm 1 \mathrm{bA}$	$59\pm1~\mathrm{aA}$	$60 \pm 1 \text{ abA}$	$63\pm1bA$		
Π	$64\pm1\mathrm{aA}$	$67\pm1\mathrm{aA}$	$68\pm2aA$	$60 \pm 1 \text{ aA}$	$64\pm1\mathrm{bA}$	$67 \pm 1 \text{cA}$	$58\pm1\mathrm{aA}$	$61 \pm 1 \text{ abA}$	$63\pm1\mathrm{bA}$		
III	$63\pm1aA$	$65\pm1\mathrm{aA}$	$70 \pm 1 \mathrm{bA}$	$61\pm1\mathrm{aA}$	$64\pm1\mathrm{bA}$	$67 \pm 1 \text{cA}$	$59\pm1\mathrm{aA}$	$61 \pm 1 \text{ abA}$	$65\pm2bA$		
IV	$63\pm1\mathrm{aA}$	$66 \pm 1 \mathrm{bA}$	$69 \pm 1 \mathrm{cA}$	$60\pm1~\mathrm{aA}$	$62\pm1~\mathrm{aA}$	$66 \pm 1 \mathrm{bA}$	$59\pm1\mathrm{aA}$	$60 \pm 1 \text{ abA}$	$63 \pm 1 bA$		
				I	Days to headin	g					
Ι	$100\pm1aA$	$\begin{array}{c} 107\pm2\\ abA \end{array}$	$110\pm3bA$	$100\pm2~aA$	$101\pm3aA$	$106\pm2~aA$	93 ±2 aA	$96\pm2aA$	$102\pm1bA$		
Π	$114\pm4~aB$	$123\pm2aB$	$123\pm4~aB$	$101\pm3~\text{aA}$	$\begin{array}{c} 108\pm3\\ abA \end{array}$	$\begin{array}{c} 114\pm3\\ bAB \end{array}$	$106\pm0\ aB$	$108\pm0bB$	$113\pm0~\text{cB}$		
III	$134\pm4~aC$	$129\pm3aB$	132 ± 5 aBC	$113\pm1aB$	$119\pm2~aB$	120 ± 4 aBC	$106\pm2aB$	$107\pm2aB$	$111\pm2~aA$		
IV	$131\pm2~\text{aC}$	137 ± 2 abC	$141\pm3bC$	$110\pm 2~aB$	$119\pm2bB$	$127 \pm 2 \text{ cC}$	$103\pm3aB$	$99\pm3aA$	$105\pm2~aB$		
				Ι	Days to anthesi	is					
Ι	$117\pm2\mathrm{aA}$	$123\pm2~aA$	$122\pm3~aA$	$112\pm2~aA$	$113\pm3~aA$	$118\pm3~\text{aA}$	$111\pm3~\mathrm{aA}$	$105\pm2~\text{aA}$	$112\pm3~\text{aA}$		
Π	$126\pm1~\mathrm{aB}$	129 ± 1 abA	$131\pm2bB$	$109\pm2aA$	$114\pm4aA$	$123\pm1bA$	$112\pm1~aB$	$114\pm2aB$	120 ± 2 bBC		
III	$148\pm4~\text{aC}$	$143\pm3~\text{aB}$	$149\pm2~aC$	$126\pm1~\mathrm{aB}$	$133\pm1~\mathrm{aB}$	$133\pm4~\mathrm{aB}$	$119\pm1~\text{aC}$	$122\pm0bC$	$125\pm0~\text{cC}$		
IV	$144\pm 2~aC$	149 ± 2 abB	$154 \pm 3 \text{ cC}$	$124\pm2~aB$	$133\pm1bB$	$140\pm2cB$	$117 \pm 1 \text{ aC}$	118 ± 1 aBC	117 ± 2 aAB		
				Days to	physiological	maturity					
I	$143\pm2\mathrm{aA}$	$152 \pm 1 \mathrm{bA}$	$157 \pm 1 \mathrm{bA}$	$144 \pm 2 \text{ aA}$	$151 \pm 1 \mathrm{bA}$	$154\pm1\mathrm{bA}$	$141 \pm 1 \text{ aA}$	$142 \pm 1 \text{ aA}$	$147 \pm 1 \mathrm{bA}$		
Π	$154\pm1~\mathrm{aB}$	$159\pm2~aB$	$164\pm2bB$	$143\pm1~\mathrm{aA}$	$149\pm1\mathrm{aA}$	$144\pm 6~\mathrm{aA}$	$140\pm1~\mathrm{aA}$	$142\pm1~\mathrm{aA}$	$148\pm1\mathrm{bA}$		
III	$169\pm2~aC$	$172\pm2~aC$	$177 \pm 1 \mathrm{bC}$	$153\pm2sB$	$162\pm3bB$	$168\pm3bB$	$154\pm5\mathrm{aB}$	$154\pm1~\mathrm{aC}$	$157\pm1~\mathrm{aB}$		
IV	$171\pm2~aC$	$184\pm1b\text{D}$	$190\pm1cD$	$157\pm2~aB$	$164\pm1\text{bB}$	$173\pm2cB$	$144\pm1aA$	$146\pm1aB$	$150\pm1bA$		

Table 3. Effects of irrigation regimes on phenological traits of wheat cultivars sown on different dates.

Values are means of six replicates from two growth cycles followed by standard errors of means (n = 6). In a row under each parameter and showing dates, means with different lowercase letters show significant differences between wheat cultivars, and in each column, values with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering and booting stages; III—irrigations at tillering, booting, and flowering stages; IV—irrigations at tillering, booting, flowering, and grain filling stages.

> Increasing irrigation frequency generally delayed jointing, heading, anthesis, and physiological maturity. For days to tillering, 18A-2 took more days than the local and 18A-1 cultivars at all sowing dates, and the number of days to tillering was reduced with delayed sowing (Table 3). Similarly, days to jointing also decreased with delayed sowing but were significantly higher for the 18A-2 cultivar at all sowing dates. Days to heading increased with irrigation frequency remained higher for the hybrid wheat cultivars and decreased with delay in sowing. Days to anthesis were the highest for 18A-2, which decreased from 154 to 117 days upon delayed sowing from 15th November to 15th December under the irrigation regime IV. Except for the 15th December sowing date, the numbers of days to physiological maturity for the 18A-2 cultivar were significantly higher than the local and 18A-1 cultivars; they increased with irrigation frequency but decreased with delay in sowing (Table 3). At the 15th November sowing date, the 18A-2 cultivar required a greater number of days for grain filling under each moisture regime (Figure 2a). However, the same was true only for irrigation regimes I and III, whereas under the most frequent irrigation regime IV, both wheat hybrids required a smaller number of days for grain filling than the local cultivar (Figure 2b). At the 15th December sowing date under the IV moisture regime, the 18A-2 cultivar took a significantly higher number of days for grain filling compared to the local and 18A-1 cultivars (Figure 2c).

45

40

35

45

40

35 AB

45

40

35

Days for graing filling

Days for graing filling

(b) 30 Nov

a^B aB

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Irrigation regimes

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Days for graing filling

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Figure 2. Effects of irrigation regimes on days for grain filling of wheat cultivars sown on different dates. Bars show mean values of six replicates from two growth cycles and contain standard errors of means (n = 6). In each panel, bars under each irrigation regime with different lowercase letters show significant differences between wheat cultivars, and bars of each cultivar with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering and booting stages; III—irrigations at tillering, booting, and flowering stages; IV—irrigations at tillering, booting, flowering, and grain filling stages. Nov = November, Dec = December.

3.2. Effects on Physiological Traits

Wheat cultivars (C), SD, and I showed significant effects on SPAD values (Figure 3; Table S2). Among the wheat cultivars and irrigation regimes, the SPAD values were significantly higher by 53.5 and 49.4% on earlier showing dates of 15th November and 30th November (Figure 3a,b) compared to the later sowing date of 15th December (Figure 3c). For the irrigation regimes, the SPAD values were recorded for IV (52.7%) followed by III (52.5%) compared to the fewer SPAD values under I. The hybrid wheat cultivar 18A-2 showed significantly higher SPAD values followed by the hybrid wheat cultivar 18A-1 compared to fewer SPAD values of local wheat cultivar, particularly on sowing dates of 30th November and 15th December. Interactions between C and SD indicated that SPAD values differed among cultivars with varying sowing dates. Evaluation of chlorophyll contents with respect to the wheat cultivars and sowing dates showed that the local cultivar IBGE sown on 15th November had the highest chlorophyll contents, followed by hybrid 18A-2 sown on 15th December (Figure 3).



Figure 3. Effects of irrigation regimes on SPAD values of wheat cultivars sown on different dates. Bars show mean values of six replicates from two growth cycles and contain standard errors of means (n = 6). In each panel, bars under each irrigation regime with different lowercase letters show significant differences between wheat cultivars, and bars of each cultivar with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering and booting stages; III—irrigations at tillering, booting, flowering, and grain filling stages. Nov=November, Dec=December.

Changes in chlorophyll a, b and carotenoid contents between C, I, and SD are shown in Table 4. Experimental factors SD and I showed significant effects on chlorophyll content (Table S2). Considering wheat cultivars and deficit irrigation regimes, the average chlorophyll contents were higher on sowing dates of 15th November and 30th November than 15th December (Table 4). For the irrigation regimes, the highest chlorophyll contents were found for the IV irrigation regime followed by the III irrigation regime, whereas the lowest chlorophyll a content was observed under I. Earlier sown hybrid wheat cultivars showed significantly higher chlorophyll contents compared to the local cultivar. Moreover, chlorophyll contents decreased with the delay in sowing for local and hybrid wheat cultivars. Effects of experimental factors on chlorophyll b contents were similar to those observed for the chlorophyll contents, and only the sowing dates and irrigation regimes have significant effects on chlorophyll b contents (Tables S2 and 4). On average, the chlorophyll b contents were higher by 10.8 and 9.60% on 15th November and 30th November sowing dates compared to those on 15th December. Higher chlorophyll b contents were generally observed under the IV irrigation regime and for the hybrid wheat cultivars (Table 4). The

chlorophyll b contents also decreased with delay in sowing from 15th November to 15th December for all wheat cultivars.

Table 4. Effects of irrigation regimes on chlorophyll a, chlorophyll b, and carotenoids contents of wheat cultivars sown on different dates.

-					Chlorophyll a (mg g $^{-1}$)					
Irrigation Regimes	15 November				30 November			15 December			
	IBGE	18A-1	18A-2	IBGE	18A-1	18A-2	IBGE	18A-1	18A-2		
I	$9.13\pm0.34~\mathrm{aA}$	$9.40\pm0.38aA$	9.13 ± 0.79 a	$A9.00 \pm 0.31 aA$	$8.47\pm0.29~\mathrm{aA}$	$8.57\pm0.28~\mathrm{aA}$	$8.30\pm0.28bA$	$7.83 \pm 0.33 \text{ abA}$	$7.30\pm0.33~\mathrm{aA}$		
П	$9.27 \pm 0.28 \text{ aA}$	$9.43 \pm 0.37 \mathrm{aA}$	$9.37 \pm 0.27 \text{ aA}$	$8.87\pm0.32~\mathrm{aA}$	$9.23 \pm 0.27 \text{ aA}$	$9.40 \pm 0.32 \text{ aA}$	$7.87 \pm 0.31 \text{ aA}$	$7.90 \pm 0.29 \text{ aA}$	$7.67 \pm 0.39 \text{ aA}$		
III	$9.53 \pm 0.31 \text{ aA}$	$9.93 \pm 0.27 \text{ aA}$	$9.57 \pm 0.32 \text{ aA}$	$9.40 \pm 0.30 \text{ aA}$	$8.90\pm0.28~\mathrm{aA}$	$8.70 \pm 0.31 \text{ aA}$	$8.17 \pm 0.29 \text{ aA}$	$8.13 \pm 0.29 \text{ aA}$	$7.97 \pm 0.30 \text{ aA}$		
IV	$9.53\pm0.31~aA$	$9.93\pm0.27aA$	$10.0\pm0.28~aA$	$9.63\pm0.27~aA$	$9.50\pm030~aA$	$8.83\pm0.28~aA$	$7.87\pm0.29~aA$	$7.93\pm0.27~aA$	$7.90\pm0.27~aA$		
				(Chlorophyll b (mg g $^{-1}$)					
I	$5.03\pm0.33~\mathrm{aA}$	5.40 ± 0.32 a	$A5.00 \pm 0.34 aA$	$4.84\pm0.32~\mathrm{aA}$	$5.27\pm0.33~\mathrm{aA}$	$4.83\pm0.32~\mathrm{aA}$	$3.40\pm0.32~\mathrm{aA}$	$3.73 \pm 0.38 \text{ aA}$	$4.53 \pm 1.13 \text{ aA}$		
П	$5.38 \pm 0.32 \text{ aA}$	$7.02 \pm 0.33 \text{bB}$	$6.62 \pm 0.30 \text{bB}$	$5.38 \pm 0.32 \text{ aA}$	$7.03 \pm 0.49 \text{ bB}$	$6.65\pm0.34~\mathrm{bB}$	$5.12 \pm 0.33 \text{ aB}$	$5.15 \pm 0.31 \text{ aB}$	$4.92\pm0.40~\mathrm{aA}$		
III	$6.73 \pm 0.35 \text{ aB}$	$7.17 \pm 0.32 \text{ aB}$	$6.77 \pm 0.36 \text{ aB}$	$6.60 \pm 0.34 \text{ aB}$	$6.10 \pm 0.32 \text{ aB}$	$5.90 \pm 0.35 \text{ aB}$	$5.33 \pm 0.32 \text{ aB}$	$5.33 \pm 0.33 \text{ aB}$	$5.17 \pm 0.34 \text{ aA}$		
IV	$6.73\pm0.35~aB$	$7.13\pm0.32~\text{a}$	$6.77\pm0.36~aB$	$6.63\pm0.33~aB$	$6.60\pm0.34~aB$	$6.03\pm0.32\ aB$	$5.07\pm0.33~aB$	$5.13\pm0.32aB$	$5.10\pm0.32~aA$		
					Carotenoids (mg g $^{-1}$)						
I	$6.17\pm1.66~\mathrm{aA}$	$7.77 \pm 1.85 \mathrm{aA}$	$6.93\pm1.28~\mathrm{aA}$	$7.27\pm2.00~aA$	$6.30\pm1.40~aA$	$7.83\pm1.55~\mathrm{aA}$	$6.90\pm1.89~\mathrm{aA}$	$6.80\pm1.54~\mathrm{aA}$	$7.10 \pm 1.33 \text{ aA}$		
П	$7.20 \pm 1.98 \text{ aA}$	$8.13 \pm 1.96 \text{ aA}$	$8.40 \pm 1.73 \text{ aA}$	7.17 ± 1.97 a	A7.93 ± 1.90 aA	$8.40\pm1.74~\mathrm{aA}$	$6.63 \pm 1.81 \text{ aA}$	7.10 ± 1.64 aA	$7.50\pm1.45~\mathrm{aA}$		
III	$7.63 \pm 2.12 \text{ aA}$	$8.10\pm1.95\mathrm{aA}$	$8.30 \pm 1.70 \text{ aA}$	$7.72\pm2.14~\mathrm{aA}$	$7.88 \pm 1.90 \text{ aA}$	$8.03 \pm 1.62 \text{ aA}$	$6.78 \pm 1.84 \text{ aA}$	$7.13\pm1.64~\mathrm{aA}$	$7.42\pm1.42~\mathrm{aA}$		
IV	$7.63\pm2.12~aA$	$8.40\pm2.04~aA$	$8.30\pm1.70~aA$	$7.85\pm2.21~aA$	$7.88\pm1.87~aA$	$8.35\pm1.76~\text{aA}$	$6.78\pm1.87~\mathrm{aA}$	$7.13\pm1.66~aA$	$7.42\pm1.43~aA$		

Values are means of six replicates from two growth cycles followed by standard errors of means (n = 6). In each panel, bars under each irrigation regime with different lowercase letters show significant differences between wheat cultivars, and bars of each cultivar with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering, booting, and flowering stages; IV—irrigations at tillering, booting, and grain filling stages.

Despite noticeable variations in carotenoids contents with respect to C, I, and SD, none of these main experimental factors showed significant effects on carotenoids contents (Tables S2 and 4). However, carotenoids contents were higher in hybrid wheat cultivars and decreased with delay in the sowing dates.

3.3. Effects on Crop–Water Relations

Relative water contents (RWC) varied significantly with SD and I experimental factors (Figure 4; Table S2). The hybrid wheat cultivar 18A-1 showed significantly higher RWC, followed by the 18A-2 and local cultivars, respectively (Figure 4a-c). The IV irrigation regime consisting of irrigation at four times over the growth period (tillering, booting, flowering, and grain filling stage) resulted in the highest RWC followed by the irrigation regime III (omitting irrigation at grain filling stage), whereas the lowest RWC was found in plots under irrigation regimes I and II receiving irrigation twice at tillering and booting stages and once only at the tillering stage, respectively. Delay in sowing beyond 15th November significantly reduced RWC. Except for C, the effects of experimental factors and their interactions were significant on WSD (Table S2). Increasing irrigation frequency under I to IV irrigation regimes consistently and significantly decreased WSD for the local wheat cultivar but not always for the hybrid wheat cultivars (Figure 4d–f). The maximum WSD values were observed under irrigation regime I for local cultivar; however, sowing dates induced significant variations in WSD. On an average basis, sowing on 15th November or 30th November resulted in lower WSD than sowing on 15th December. The results showed that the highest WSD was found for the hybrid wheat cultivar 18A-2 under irrigation regime II sown on 30th December (Figure 4e).



Figure 4. Effects of irrigation regimes on RWC, WSD, WUC, and WRC in wheat cultivars sown on different dates. Bars show mean values of six replicates from two growth cycles and contain standard errors of means (n = 6). In each panel, bars under each irrigation regime with different lowercase letters show significant differences between wheat cultivars, and bars of each cultivar with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering and booting stages; III—irrigations at tillering, booting, and flowering stages; IV—irrigations at tillering, booting, flowering, and grain filling stages. Nov = November, Dec = December.

The data on crop–water relations showed that WUC was influenced significantly by experimental factors C, SD, and I (Table S2). The local cultivar IBGE showed significantly higher WUC than the hybrid cultivars, and among these hybrid cultivars, 18A-1 had fewer WUC values than 18A-2 (Figure 4g–i). The irrigation regime IV resulted in significantly lower WUC values compared to other irrigation regimes. Delay in sowing time drastically increased WUC. Sowing the wheat cultivars on 15th November had the lowest WUC values in contrast to the highest WUC values on 15th December. In contrast to RWC, WSD, and WUC, none of the experimental factors induced significant effects on WRC (Table S2). The data further showed the non-consistent variations in WRC values (Figure 4j–l).

3.4. Effects on Biological and Grain Yields

The effects of C, SD, and I are shown in Figure 5 and Table S2. The biological yield of hybrid wheat cultivars was always significantly higher than the local cultivar at all sowing dates, and the 18A-2 cultivar showed the highest biological yield (Figure 5a–c). Biological yield for each cultivar decreased with a delay in sowing time from 15th November to 15th December. The hybrid wheat cultivars consistently produced higher biomass compared to the local cultivar under all irrigation regimes at each sowing date; however, the differences between the two hybrid wheat cultivars were not always significant. Trends in the effects

of main factors C, SD, and I on grain yield were similar to those of biological yield and were always significant (Table S2). Grain yield of hybrid wheat cultivars was higher than the local cultivar, whereas 18A-2 cultivar produced the highest grain yield at all sowing dates (Figure 5d–f). When sown earlier on 15th November, grain yield of 18A-2 cultivar was the highest under the irrigation regimes III and IV, and similar effects were found for the sowing date of 30th November. On 15th December sowing date, differences of grain yield between irrigation regimes for each cultivar were non-consistent, but the grain yield remained the highest for the 18A-2 cultivar under III and IV irrigation regimes (Figure 5f).



Figure 5. Effects of irrigation regimes on biological and grain yields of wheat cultivars sown on different dates. Bars show mean values of six replicates from two growth cycles and contain standard errors of means (n = 6). In each panel, bars under each irrigation regime with different lowercase letters show significant differences between wheat cultivars, and bars of each cultivar with different uppercase letters show significant differences between irrigation regimes at p < 0.05. I—irrigation at tillering stage; II—irrigations at tillering and booting stages; III—irrigations at tillering, booting, and flowering stages; IV—irrigations at tillering, booting, flowering, and grain filling stages. Nov = November, Dec = December.

3.5. Correlations of Biological and Grain Yields with Crop Traits

The relationships of biological and grain yields with SPAD values, days to maturity, and days to grain filling are showed in Figure 6. The biological and grain yields were significantly positively correlated with SPAD values (Figure 6a,b). The relationships of biological and grain yields with days to maturity were significant positive and were much stronger (Figure 6c,d). However, the correlations of biological and grain yields with days for grain filling were negative and non-significant (Figure 6e,f).



Figure 6. Correlations of biological and grain yields with SPAD values, days for maturity, and days for grain filling.

4. Discussion

This study observed that the irrigation regimes and sowing dates significantly influenced the chlorophyll traits, i.e., SPAD values, chlorophyll a and b contents, and carotenoids of wheat hybrids. Irrigation, cultivar and crop management practices can affect the chlorophyll contents, which alter the other physiological attributes of plants. Chlorophyll molecules are the main component and are essential for harvesting light energy in photosynthesis and all physiological responses [40]. Thomas et al. [41] noticed that chlorophyll contents play a dominant role in achieving a higher photosynthetic rate and showed a significant and positive correlation between photosynthetic rate and SPAD values. As the sowing intervals are delayed, greater variations occur among the cultivars for chlorophyll contents [42]. The accumulation of both chlorophyll a and b contents decreased under stressed conditions [43]. Chlorophyll a and b molecules have distinct characteristics based on their varying chemical structures, which enable them to absorb specific infrared light by acting as photoreceptors and perform photosynthetic functions to convert sunlight into chemical energy [44,45]. Irakli et al. [46] reported that chlorophyll contents reduced under abiotic stress such as water, light, and salinity. The drought-tolerant wheat cultivars showed much higher chlorophyll a and b contents and better morpho-physiological traits under water-deficit conditions, which served as important characteristics for hybrid cultivar development [47]. The SPAD values in our study were significantly influenced by cultivars, sowing dates, and irrigation regimes, and they were significantly positively correlated with biological and grain yields. The SPAD values generally reflect the chlorophyll contents in leaves and are a reliable indicator of plant growth, development, and physiological health under diverse growth conditions [48,49]. Ayer et al. [50] also demonstrated significant positive relationships of SPAD values with biological and grain yields and harvest index for various wheat genotypes.

In this study, late sowing hastened booting, heading, anthesis, and maturity, and it caused a significant reduction in yield and yield components of wheat but much less for the hybrid cultivars. Moreover, the local cultivar required significantly less time to complete phenological growth stages for different sowing dates than the hybrid cultivars, which directly influenced their performance and adaptability. The presence of environmental stresses such as drought, moisture, and temperature can have pronounced effects on the plant developmental stages, including germination, tillering, booting, heading, anthesis, and maturity [51]. On the late sowing dates, a rise in temperature may impair the grain filling stage [51]. We found that the hybrid wheat cultivars exhibited a prolonged grain filling period than the local cultivars suggesting means more time for photosynthate accumulation in the grains and, ultimately, higher yield grain yields [52,53]. These observations are supported by the positive relationships of biological and grain yields with SPAD values and days for maturity. Our findings are also consistent with Hossain and Da Silva [54], who reported that the late-sown wheat faced high-temperature stress at later growth stages, completed heading, grain filling, and grain maturity earlier than early sown wheat crop, and resulted in fewer grain yields. For the late-sowing dates, the inferior growth of the local cultivar compared to the hybrid cultivars might indicate decreased photosynthesis activity, carbohydrate translocation, and assimilation [55]. Similar to our study, Mumtaz et al. [56] reported the wheat crop sown late on 21 December took below-optimal days for booting, heading, anthesis, and maturity. Late sowing can expose the crop to low temperatures at the time of emergence, delay emergence, and reduce growth rate, which leads to dwarf plants, fast heading, and less time for grain filling and maturity, and ultimately result in low biomass production and grain yield [57,58]. Conversely, our results showed that the optimum sowing time resulted in more days to tillering, jointing, heading, anthesis, and maturity, which correlated significantly positively with biological and grain yields. However, cooler temperatures have been reported to delay flowering and maturity [59,60]. Spink et al. [57] demonstrated that delayed sowing shortened the duration of each development phase due to a rise in temperature. The reason for a decrease in the anthesis days could be a high temperature in for the late-sown dates, which reduced the length of growth period. However, the temperature generally immediately increases after mid-March and may reach beyond 30 °C by the end of March along the increase in day length forcing the crop to complete the cycle rather quickly [61,62]. Therefore, the late-sown crop generally has little time for optimum growth and development. In addition, the irrigation stress can also shorten the growing period of crops and accelerate their phenological traits such as heading, booting, anthesis, and maturity [63]. The limited ability of plants for nutrient uptake and photosynthetic efficiency under heat and drought stress can also reduce organ size (leaf, tiller, and spikes) and growth periods during various development stages of tillering, jointing, booting, heading, anthesis, and grain filling [64]. The plant sensitivity to drought and high temperature may result in disturbed metabolic processes coupled with a shorter plant life cycle and, consequently, reduce plant biomass accumulation and grain yield [65–67]. However, our study showed that the hybrid wheat cultivars were better adapted to these stresses and performed better than the local cultivar in Pakistan.

The crop–water traits of wheat hybrids, i.e., RWC, WSD, WUC, and WRC, were significantly affected by deficit water irrigation regimes and sowing dates in our study. Osmotic adjustment is a process of accumulating solutes in plants for lowering soil water potential to alleviate the negative effects of water stress and, thus, increase the permeability of cells [68,69]. Relative water content is considered to be an essential indicator of water stress in leaves and shows a direct relationship to soil water contents. Ranney et al. [70] reported that the osmotic adjustment mechanism reduces the osmotic potential of cells and maintains the turgor of tissues under water stress. Our study showed that hybrid wheat cultivars adapted efficiently to reduced water availability by possibly improving crop–water relations under deficient irrigation primarily due to maintenance of cell turgor and osmotic potential [71–73]. When the rate of transpiration exceeds the absorption process, it results in decreased water content in leaves, and ultimately, cell volume, stomatal

conductance, and relative water content are decreased due to low cell turgor [74]. Blum [75] showed that enhancing transpirational efficiency under deficient and optimum moisture conditions can improve WUE and crop productivity under dryland conditions. Leaf tissue turgor pressure is controlled by the process of leaf water content and helps to maintain leaf activity for the maximum photosynthetic rates [76,77]. Our study showed that higher WUC, WSD, and WRC could be attained by irrigation given at once, whereas more availability of water to the crop reduced the WUC, WSD, and WRC in wheat crop [64]. Similar to our findings, Guendouz et al. [78] showed that irrigation conditions and WUE strongly influenced the grain yield of durum wheat cultivars. Improved crop–water relationships offer substantial opportunities to improve WUE by using deficit irrigation, soil water, and nutrient management approaches under varying agro-climatic conditions [79,80].

Our study showed that wheat cultivars, irrigation regimes, and sowing dates significantly affected wheat biomass production and grain yield. Wheat crop sown at appropriate time generally results in higher biological and grain yields, which show linear relationships with photosynthetic activity, plant productivity, and grain yields [57,81]. Hussain et al. [82] noticed hindrance in germination process and crop growth rate with delay in sowing, which resulted in a reduced number of tillers m⁻², biomass production, and yield. In the present study, we also found a substantial decrease of 44% in grain yield with delay in sowing from 15th November to 30th November and further delay to 15th December reduced yield by 27% across both the local and hybrid wheat cultivars. The decrease in grain and biological yield with delay in sowing might be due to the rise in temperature at reproductive phase that decreased the photosynthate assimilation efficiency and the number of productive days [83]. Such reduction in grain and biological yield due to the delayed sowing has also been reported previously [84-86]. Irrigation regimes coupled with sowing dates are important factors influencing crop yield and yield contributing traits, and water stress can adversely affect the number of grains spike⁻¹, tillers m⁻², and biomass production [87,88]. We found that the decrease in crop yield under deficit irrigation may be due to the production of fewer photosynthates and translocation of the assimilate to the competitive sink. The optimal irrigation required at critical stages increased crop biological and grain yields due to maximum photosynthates production in leaves. This could lead to better development of grains under optimal nutrients supply because water deficiency causes reverse osmosis resulting in lower grain and biological yields [89,90]. Prey et al. [91] compared the nitrogen use efficiency and C allocation potential of high yield hybrid wheat cultivars with local wheat breeds to show that hybrid cultivars produced higher grain yields attributed to higher harvest index, post-anthesis photosynthate assimilation, and grains per spike. Zhou et al. [92] found higher grain yields of hybrid rice due to improved WUE and crop-water relationships under water-deficit conditions. In addition to deficit irrigation, micro-irrigation, deficit drip irrigation, and planting patterns can also enhance WUE under drought-prone conditions [93–95]. However, productivity and WUE of hybrid crop cultivars can also strongly depend on agronomic practices and climatic conditions, e.g., Buczek [96] reported that grain yield and quality of hybrid wheat varied significantly with tillage practices, whereas Rezaei et al. [97] found that phenology of wheat cultivars varied climatic changes. As reported in our study, hybrid wheat can result in major yield increases and ensure food security by counterbalancing the extreme environmental conditions, including heat and drought stress [98,99]. However, despite the promising potential of the hybrid wheat cultivars under varying sowing dates and deficient moisture, large-scale adaptability and yield stability of these cultivars require more research by applying various tools such as statistical models, multi-environmental trials, and farmer surveys in Pakistan [100–102].

5. Conclusions

Cultivation and optimization of hybrid wheat cultivars to obtain higher biomass production and grain yield under less irrigation water are relatively new in the wheatgrowing belt in Pakistan. Our three-factor (wheat cultivars, sowing dates, and irrigation regimes) two-year field study showed that deficit irrigation improved the crop-water relations and crop yields. The early sowing improved RWC, chlorophyll content, and WUE under deficit irrigation as compared to the late sowing under full irrigation scenarios. The Chinese hybrid wheat cultivar 18A-2 performed better with improved crop-water relationships and higher yield under deficit irrigations. Moreover, the hybrid 18A-2 cultivar had higher chlorophyll contents when sowing early compared with the local cultivar. The hybrid cultivars took more days to maturity and grain filling. Our study further showed that both hybrid wheat cultivars produced higher biological and grain yields than the local cultivar at all sowing dates but biological and grain yields decreased with delay in sowing; however, the decline in yield with delayed sowing was more prominent in the local cultivar. Both the biological and grain yields were correlated significantly positively with SPAD values and days to maturity. Furthermore, the provision of irrigation at the three (tillering, booting, and flowering) and four (tillering, booting, flowering, and grain filling) critical growth stages resulted in the optimum biomass production and grain yield. The hybrid wheat cultivars were better adapted to deficit irrigation and delayed sowing by producing higher biomass and crop yields under semi-arid climatic conditions in Pakistan. By adopting deficient irrigation strategies, wheat crop was protected against water deficiency as well as over-irrigation and resulted in water saving both with and without rainfall. This study reports pioneer work on hybrid wheat cultivation under semi-arid climatic conditions of Pakistan and, therefore, more work is required to test the potential of hybrid wheat on a wider scale for its adaptability, yield-stability, profitability, and commercialization.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/ 10.3390/agronomy11101976/s1, Table S1: Historical weather conditions at the study site; Table S2: F statistics of linear mixed models for the effects of wheat cultivars, sowing dates and irrigation regimes on growth and yield of wheat.

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