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Productivity of sorghum (*Sorghum bicolar* L.) at diverse irrigation regimes and sowing dates in semi-arid and arid environment

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Abstract: Determining optimal sowing date, optimal number of irrigation applications, and best-performing cultivars is critical to maximizing achievable sorghum yield in semiarid and arid environments. Limited research is available on interactive effects of sowing date, irrigation frequency, and genotype at multiple locations. Consequently, this study was conducted to determine impact of sowing dates, irrigation regimes, and cultivars on yield and growth traits during 2016 and 2017 at two locations in Pakistan. Experiments were laid out in a split–split design at Maize and Millets Research Institute, Yusafwala, Sahiwal, and at Bahauddin Zakariya University, Multan. Each experiment was comprised of three factors: (a) main plot irrigation regimes (I_0 = Two irrigations; I_1 = Four irrigations; I_2 = Six irrigations; and I_3 = Eight irrigations), (b) sub-plot varieties (V_1 = YSS 98; V_2 =Y 16; and V_3 = Lasani hybrid), and (c) sub-sub-plot sowing dates (SD_1 = 15 June; SD_2 = 1 July; SD_3 = 15 July, and SD_4 = 30 July). Results showed that effects of sowing date, irrigation regimes, and varieties on growth and sorghum yield were significant. Planting time July was far superior for studying growth traits, phenology, and yield of sorghum varieties than early planting time (15 June), for which adverse effects on all characteristics of plant traits were observed. Various irrigations levels also affected sorghum yield, but I_2 produced best results. Maximum performance index was observed in the second year of study. Decreasing productivity pattern was $I_2 > I_3 > I_1 > I_0$ for irrigation regimes, $V_3 > V_2 > V_1$ for cultivars and $SD_3 > SD_4 > SD_2 > SD_1$ for sowing dates at Sahiwal and Multan. Results revealed that germplasm resource is a need of day that can be used for future plant improvements in semiarid and arid environments.

Key words: Biomass, cereals, C_4 crop; grain yield

1. Introduction

Crop production must be enhanced to fulfil the burgeoning global population's demand for food, feed, and fibre (Shahzad and Ahmad, 2019). During the next 20 to 25 years, global food demand is expected to rise by 50%. Approximately 80% of the increased demand will be from developing countries and arid and semi-arid regions where food is already scarce (Fereres and Soriano, 2007). Greenhouse gases (GHGs) and their variability are impacting on water supply, and as a result, are a significant threat to national, regional, and global food security (Ray et al., 2019; Sarwar et al., 2021; Naz et al., 2022). Cropping systems must become more resilient to future climate uncertainty to increase food security and, eventually, standards of livelihoods (Hatfeld and Prueger, 2015). However, widespread yield differences have been identified across agricultural systems in semiarid and arid regions due to inadequate water management practices (Miriti et al., 2012). Climate change is a well-known fact that has negative consequences for biodiversity, forest, agriculture, human health, and socio-economic sectors (Evans and Sadler, 2008). The Intergovernmental Panel on Climate Change (IPCC) estimates that developing countries and least developed are most vulnerable to the destructive effects of climate change and are likely to suffer more in the future (IPCC, 2013, 2019). Developing nations will also face natural resource degradation and restricted access to current information on climate change (Garces-Restrepo et al., 2007). Furthermore, Baptists and Naylor (2009) reported that potential climatic conditions are significant determinants of agricultural production systems contributing to food insecurity in many countries.

Grain sorghum is a C_4 plant and a hardy crop for arid-zone farmers because it can withstand drought and meet the high demand for animal feed and ethanol production. In arid and semiarid areas, farmers sow early and late

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hybrids, and they often apply deficit irrigation (Evett et al., 2012). Thus, sorghum is a suitable choice for farms with limited water supply, and it works well with other crops in diverse rotations (Baumhardt et al., 2007).

Under ideal crop husbandry, varieties having high productivity potential can play a critical role in increasing productivity (Gorbacheva et al., 2010). Due to genetic variations, different varieties of sorghum crops respond differently to growing conditions. At present, the growth of drought tolerant and heat tolerant cultivars are critical to obtaining maximum grain yield under arid environmental conditions (Ezzat et al., 2010). Therefore, heat- and drought-resistant water-efficient sorghum varieties with high grain potential should be bred for the farms in these regions to reach high sorghum crop productivity (Mukondwa et al., 2021). Heat and drought tolerance around the anthesis, optimal canopy structure and phenology, improved root water uptake and reduced leaf senescence under drought conditions are essential factors for the growth of appropriate sorghum crop cultivars (Ndiaye et al., 2019).

Environmental demand is one factor in determining the optimum sowing date of a sorghum crop; it is critical to avoid various types of biotic and abiotic stresses. For example, a sorghum crop sown at the recommended time, which in Punjab, Pakistan, is from March to September for a fodder crop and in July for a grain crop (http://www.agripunjab.gov.pk), matures at the optimum time after passing through its vegetative and reproductive phases and has a better growth rate than a sorghum crop sown later in the season (Choi et al., 2019). An optimum sowing date results in maximum grain yield. It helps plants avoid severe stress from a water deficit and related biotic and abiotic stresses (such as heat, diseases, and pests) that become more dominant, as the sorghum crop season advances under arid environmental conditions (Alshikh et al., 2017).

There are few published reports on the effect of sowing time on the phenology of sorghum varieties and grain yield under different irrigation conditions and different environments (Chapman et al., 2000; Fatima et al., 2018, 2020; Shahzad and Ahmad, 2019; Koláčková et al., 2020). Therefore, this research focused on evaluating the response of sorghum cultivars to different irrigation regimes and planting dates under the agro-ecological conditions of semiarid at Sahiwal and arid at Multan in Punjab province, Pakistan.

2. Materials and methods

2.1. Experimental sites

The experiments were carried out in 2016 and 2017 at the Maize and Millets Research Institute (MMRI), Yusafwala, Sahiwal (30.68° N, 73.21° E), and the experimental area of the Bahauddin Zakariya University (BZU), Multan (30.27° N, 71.50° E), in Pakistan. Soil samples were taken prior to crop sowing to analyze the physico-chemical characteristics. Subsequently, the samples were air-dried, sieved, and mixed thoroughly to make a composite sample. The working sample was taken from the composite sample to measure the physico-chemical properties of the study sites. The soil analysis for the study sites is presented in Table 1 (Mubarik, 2021). The observed climatic data of study sites are presented in Figure 1. At Sahiwal, the mean monthly maximum temperature ranged from 33.9 to 39.9 °C, while the mean monthly minimum temperature ranged from 19.2 to 28.9 °C. The mean monthly sunshine ranged from 7.00 to 9.38 h. The photoperiod ranged from 11.45 to 12.93 h during the vegetative phase and from 13.09 to 14.16 h during the reproduction phase. The total rainfall for the 2016 and 2017 crop seasons was 315 mm and 329

Table 1. The physio-chemical characteristics of soils of each research site.

Soil parameters	Multan		Sahiwal	
	2016	2017	2016	2017
Sand	60	58	55	53
Silt	18	15	15	16
Clay	22.00	27.80	30	31
pH	7.01	7.19	7.45	7.73
EC (dSm^{-1})	1.34	1.39	1.56	1.64
Nitrogen (ppm)	19.32	17.87	21.81	20.31
Phosphorus (ppm)	6.30	6.21	6.01	6.12
Potassium (ppm)	144.34	141.23	125.43	129.34

Source: Mubarik (2021)

mm, respectively. At Multan, the mean monthly maximum temperature ranged from 33.74 to 39.8 °C, while the mean monthly minimum temperature ranged from 20.29 to 31.11 °C. The mean monthly sunshine ranged from 4.50 to 9.12 h. The photoperiod ranged from 11.20 to 12.72 h during the vegetative phase and 12.92 to 14.01 h during the reproduction phase. The total rainfall for the 2016 and 2017 crop seasons was 81 mm and 155 mm, respectively (Figure 1).

2.2. Experimental details

The sorghum cultivars (YSS 98, Y 16 and Lasani hybrids) were procured from the Maize and Millets Research Institute (MMRI) Sahiwal, Pakistan and the National Agricultural Research Center (NARC), Islamabad, Pakistan. Each research treatment was repeated three times, and the experiment included three factors: (a) main plot irrigation regimes (I_0 = Two irrigations; I_1 = Four irrigations; I_2 = Six irrigations; I_3 = Eight irrigations), (b)

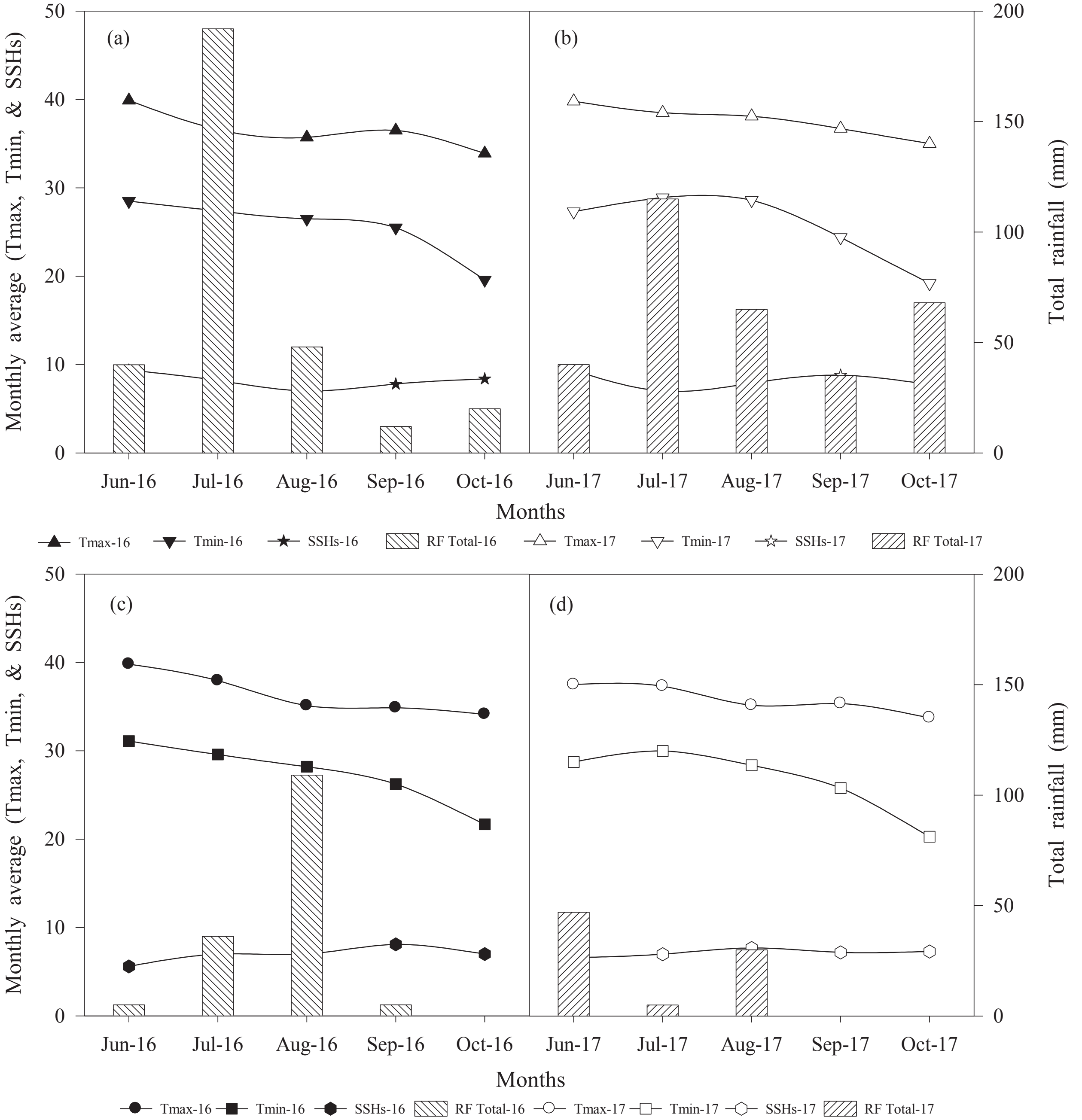

Figure 1. Mean monthly maximum and minimum temperatures, sunshine hours, and total monthly rainfall at the study site (a, b Sahiwal) and (c, d Multan) during 2016 and 2017.

sub-plot cultivars (V_1 = YSS 98; V_2 = Y16; and V_3 = Lasani hybrids), and (c) sub-sub-plot sowing dates (SD_1 = 15 June; SD_2 = 1 July; SD_3 = 15 July, SD_4 = 30 July). Concerning irrigation regimes, the water application quantity for each irrigation was 75 mm. The total quantity of irrigation water applied for treatment at both locations was 150 mm, 300 mm, 450 mm, and 600 mm for two, four, six, and eight irrigations, respectively. Water samples were taken, and the Punjab government testing laboratory performed the analysis. The EC value was 950 µS/cm at Sahiwal, and 1125 µS/cm at Multan. The Sodium Absorption Ratio (SAR) was 4.5 at Sahiwal and 5.2 at Multan. Chloride values were 251 mg/L at Sahiwal and 272 mg/L at Multan. The sorghum cultivars characteristics of YSS 98, Y 16, and the Lasani hybrid differ slightly; yield potential of YSS 98, Y-16 and the Lasani hybrid is 5039, 6220, and 6500 kg ha^{-1}, respectively. The YSS 98 variety is tall, sweet, medium-duration, medium-yielding, and dual-purpose (grain and fodder). The Y-16 has a low HCN level and is tall, long duration, high-yielding, of medium lodging resistance and more widely adaptable. The Lasani hybrid is tall, sweet, long duration, high yielding, high lodging resistance and tolerant to insect pests and diseases. It has semierect leaves and stays green.

2.3. Crop management

At both sites, sorghum was planted using a hand drill for sowing in rows 30 cm apart. The seed rate was 15 kg ha^{-1}. Thinning was carried out to maintain optimum planting density prior to the first irrigation. Nitrogen and phosphorus were applied at 80 and 60 kg ha^{-1}, respectively. The sorghum was harvested when the grains contained 20%–25% moisture.

2.4. Observations, measurements, and data analysis

A total number of ten plants from each plot were tagged, and all the yield attributes were recorded using standard or approved protocols (Ahmad et al., 2016a, b; http://www.agripunjab.gov.pk). The sorghum plant height, head length, and internodal length were recorded by using a meter rod. When sorghum plants reached maturity, two rows were harvested from each field, made into small bales, and dried in the sun for a week. Then, the biomass of the samples collected from each field was calculated using a balance and measured in tons/ha. After threshing, the overall seed yield per plot was measured using an electric balance and then the measurement was converted to kg/ha. From these plots, 1000 healthy and normal seeds were obtained per treatment and weighed with an electric balance. The harvest index (HI) was computed by dividing seed productivity by the total biological yield and multiplying that figure by 100.

2.5. Statistical analysis

Statistix 8.1 was used for statistical evaluation utilizing RCBD with a factorial arrangement. A least significance difference test (5% probability) was employed to compare treatments (Steel et al., 1997).

3. Results

The factors employed in the current study, such as planting dates, irrigation regimes, and cultivars significantly affected plant height and panicle length at both locations during the study period, as shown in Table 2. The results for all individual factors for plant height and panicle length were significant; however, the results for all interactive effects were nonsignificant except I × V at Sahiwal in 2017, and V × SD and I × V × SD at both locations in both years. For the sorghum varieties studied, the tallest plant height was attained for Lasani, followed by Y16 and YSS 98 at the two sites. Regarding the sowing dates for both years at both locations, the tallest sorghum height and longest panicle length were attained for the 15 July sowing date (SD_3). At Sahiwal, the tallest sorghum heights were measured as 194.7 and 195.0 cm in 2016 and 2017, respectively, and the longest panicle lengths measured as 15.5 and 16.4 cm in 2016 and 2017, respectively. At Multan, the tallest sorghum heights were measured as 192.8 and 194.1 cm in 2016 and 2017, respectively, and the longest panicle length measured as 14.7 and 15.5 cm in 2016 and 2017, respectively. At both locations and for both years, the shortest plant height and panicle length were observed in SD_1. Regarding irrigation regimes, at Sahiwal, the tallest plant height (201.2 and 201.9 cm for 2016 and 2017, respectively) and the longest panicle length (16.2 and 17.1 cm for 2016 and 2017, respectively) were recorded for six irrigations (I_2), followed by eight irrigations (I_3), which were statistically at par in both years. Similar irrigation results were observed at Multan for plant height and panicle length for both years. The shortest plant height and panicle length were observed for two irrigations (I_0) at Sahiwal and Multan in 2016 and 2017. For the interaction effects I × V and I × SD, the tallest sorghum height and longest panicle length were observed for the Lasani hybrid planted on 15 July for I_2 at Sahiwal and Multan (Figure 2 and Figure 3; A-D).

Statistically significant results regarding stem diameter were observed for the date of sowing, irrigation levels, and sorghum cultivars (depicted in Table 3) at Sahiwal and Multan in both years. However, interactive effects were nonsignificant except V × SD and I × V × SD at both locations in both years.

The widest stem diameter for the sorghum varieties studied at the two sites was observed in the Lasani hybrid, followed by Y16 and YSS 98. Regarding the sowing dates, the widest stem diameter in 2016 and 2017 at both locations was observed on the 15 July sowing date (SD_3) followed by SD_4, followed by SD_2. The narrowest stem diameter was recorded in SD_1 at Sahiwal and Multan in 2016 and 2017. Regarding irrigation levels, the widest stem diameter and longest inter-nodal length were observed for

Table 2. Impact of different irrigation regimes and sowing dates on the plant height & panicle length (cm) of various sorghum cultivars.

Experimental Treatments	Plant Height (cm)				Panicle Length (cm)			
	Sahiwal		Multan		Sahiwal		Multan	
Irrigation Levels (I)	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
I_0 = 2 Irrigation	171.9 C	173.3 C	169.0 C	172.3 C	12.7 C	13.1 C	11.8 C	12.3 C
I_1 = 4Irrigation	181.3 B	182.7 B	179.4 B	181.7 B	14.6 B	15.2 B	13.1 B	14.3 B
I_2 = 6Irrigation	201.2 A	201.9 A	198.3 A	201.6 A	16.2 A	17.1 A	15.2 A	16.0 A
I_3 = 8Irrigation	199.1 A	202.5 A	199.9 A	199.6 A	15.9 A	16.3 A	14.9 A	15.5 A
LSD (I) ($p \leq 0.05$)	**4.15**	**4.67**	**1.45**	**2.94**	**0.41**	**0.55**	**0.34**	**0.91**
Sorghum Varieties (V)								
V_1 = YSS 98	184.4 C	186.2 C	182.5 C	183.8 C	12.7 C	13.6 C	11.8 C	12.5 C
V_2 = Y 16	188.0 B	190.3 B	186.1 B	189.4 B	14.9 B	15.1 B	14.6 B	14.9 B
V_3 = Lasani hybrid	192.9 A	195.2 A	191.0 A	192.9 A	16.7 A	17.3 A	16.1 A	16.7 A
LSD (V) ($p \leq 0.05$)	**2.43**	**3.01**	**2.91**	**2.10**	**0.91**	**1.04**	**1.56**	**1.09**
Sowing Dates (SD)								
S_1 = 15th June	181.7 D	183.4 D	179.8 D	182.1 D	14.1 D	14.7 D	13.2 D	13.7 D
S_2 = 1st July	186.4 C	187.3 C	185.6 C	186.8 C	14.6 C	15.0 C	13.8 C	14.2 C
S_3 = 15th July	194.7 A	195.0 A	192.8 A	194.1 A	15.5 A	16.4 A	14.7 A	15.5 A
S_4 = 30th July	190.8 B	192.7 B	188.9 B	191.3 B	15.2 B	15.5 B	14.1 B	15.0 B
LSD (SD) ($p \leq 0.05$)	**1.56**	**2.12**	**2.01**	**3.01**	**0.20**	**0.17**	**0.25**	**0.21**
Significance Level (I)	**	**	**	**	**	**	**	**
Significance Level (V)	**	**	**	**	**	**	**	**
Significance Level (I × V)	*	NS	**	**	*	NS	**	**
Significance Level (SD)	**	**	**	**	**	**	**	**
Significance Level (I × SD)	**	**	**	**	**	**	**	**
Significance Level (V × SD)	NS	NS	NS	NS	NS	NS	NS	NS
Significance Level (I × V × SD)	NS	NS	NS	NS	NS	NS	NS	NS

Note: Any two means followed by same letter are not significantly different; n = 3. NS = nonsignificant; ** = significant at $p \leq 0.01$

I_2, followed by I_3, which were statistically at par at Sahiwal and Multan in both years. The narrowest stem diameter was observed for I_0 at Sahiwal and Multan in 2016 and 2017. For the interactive affects I × V and I × SD, the widest stem diameter was observed for the Lasani hybrid planted on 15 July at I_2 (Figure 4; A-D).

The sowing dates, irrigation levels, and sorghum cultivars significantly affected seed weight (per 1000 seeds; depicted in Table 3) at Sahiwal and Multan in 2016 and 2017. Interactive effects were nonsignificant except V × SD, I × V × SD, and I × V at both locations during the study period. Regarding the varieties the heaviest seed weight was observed in the Lasani hybrid at Sahiwal and Multan in 2016 and 2017 followed by Y16 and YSS 98. Regarding the sowing dates, the heaviest seed weight at Sahiwal and Multan during the study period was observed in SD_3 (sown 15 July), followed by SD_4 and SD_2. The lightest seed weight per 1000 seeds was measured for SD_1 at Sahiwal (21.88 & 21.91 g in 2016 and 2017, respectively) at and at Multan (21.84 & 21.85 g in 2016 and 2017, respectively). Regarding irrigation regimes, at Sahiwal, the heaviest seed weight (23.11 and 23.14 g in 2016 & 2017, respectively) was observed for I_2 followed by I_3 statistically at par in 2016 and 2017. A similar result was observed at Multan where the heaviest seed weight (23.08 and 23.10 g in 2016 & 2017, respectively) was observed for I_2 followed by I_3 statistically at par in 2016 and 2017. Regarding irrigation regimes, the lightest seed weight was observed for I_0 at Sahiwal in 2016 and 2017. A similar result was observed at Multan. Regarding the interactive effect of I × V for the leaf area per plant, and I × V and I × SD for both leaf area per plant and seed weight was recorded for the Lasani hybrid planted on 15 July with I_2 (Figure 5 A–D).

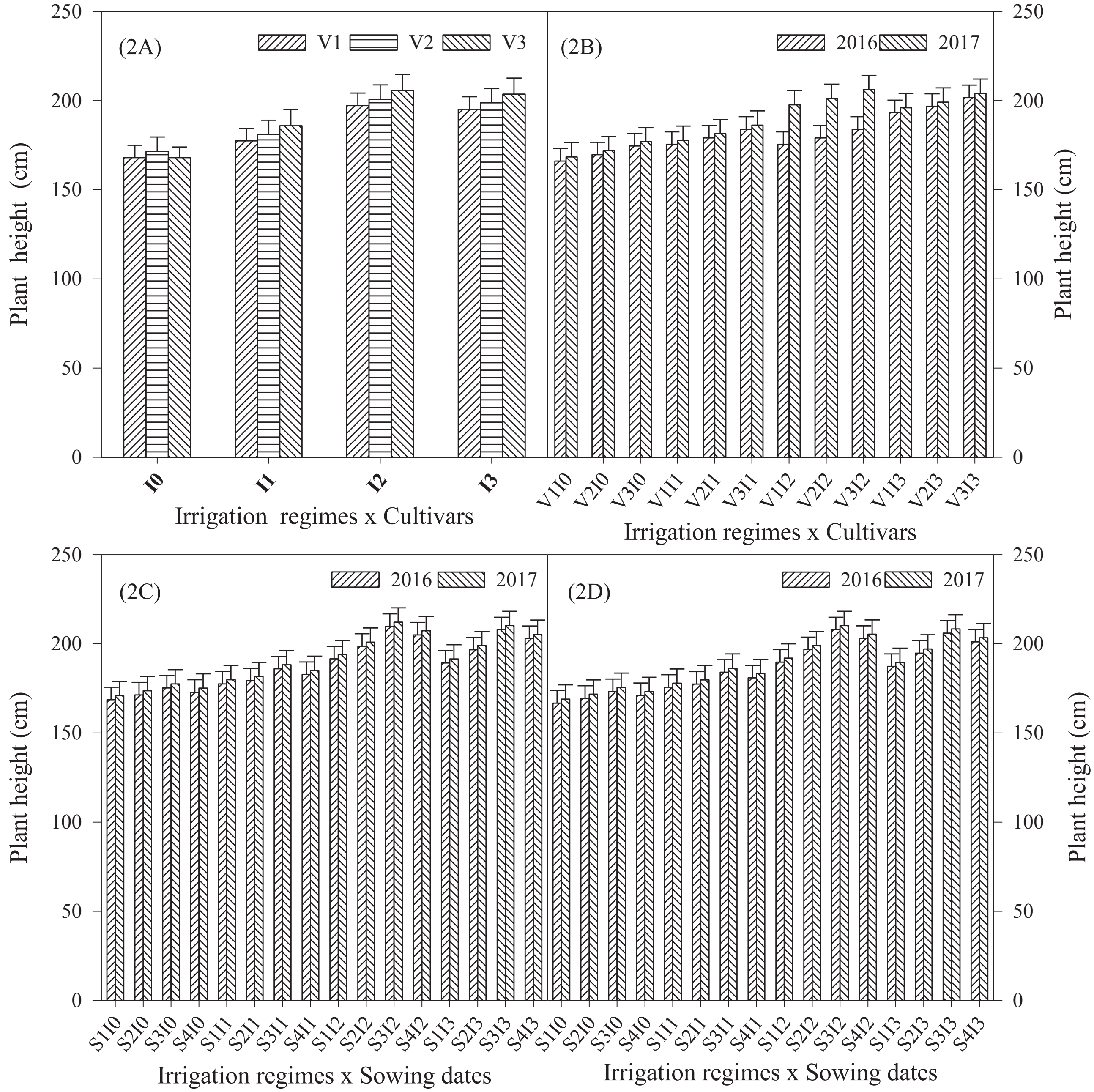

Figure 2. Interactive effect of irrigation regimes and sorghum cultivars during 2016 at Sahiwal (A), irrigation regimes and sorghum cultivars at Multan during both years (B), irrigation regimes and sowing dates at Sahiwal during 2016 (C), irrigation regimes and sowing dates at Multan during both years(D) on plant height. Bars represent SE.

All individual factors significantly affected the seed productivity, biomass production, and harvest index (HI) at Sahiwal and Multan in 2016 and 2017 (as shown in Table 4 and Table 5). The results of interactive effects were nonsignificant for seed productivity, biomass production, and HI except V × SD and I × V × SD. Regarding the sorghum varieties the highest seed productivity, biomass production, and HI were attained for the Lasani hybrid followed by Y 16 and YSS 98 at both locations in both years. At Sahiwal, the measurements were 2941.91 and 2981.85 kg ha^{-1}; 24077 and 24275 kg ha^{-1}; 48.47 and 49.46% for 2016 and 2017, respectively. At Multan, measurements were 2902.20 and 2934.21 kg ha^{-1}; 23875 and 24106 kg ha^{-1}; 46.79 and 47.56% for 2016 and 2017, respectively. Regarding the sowing dates, the highest seed productivity, biomass production, and HI at both locations for both years

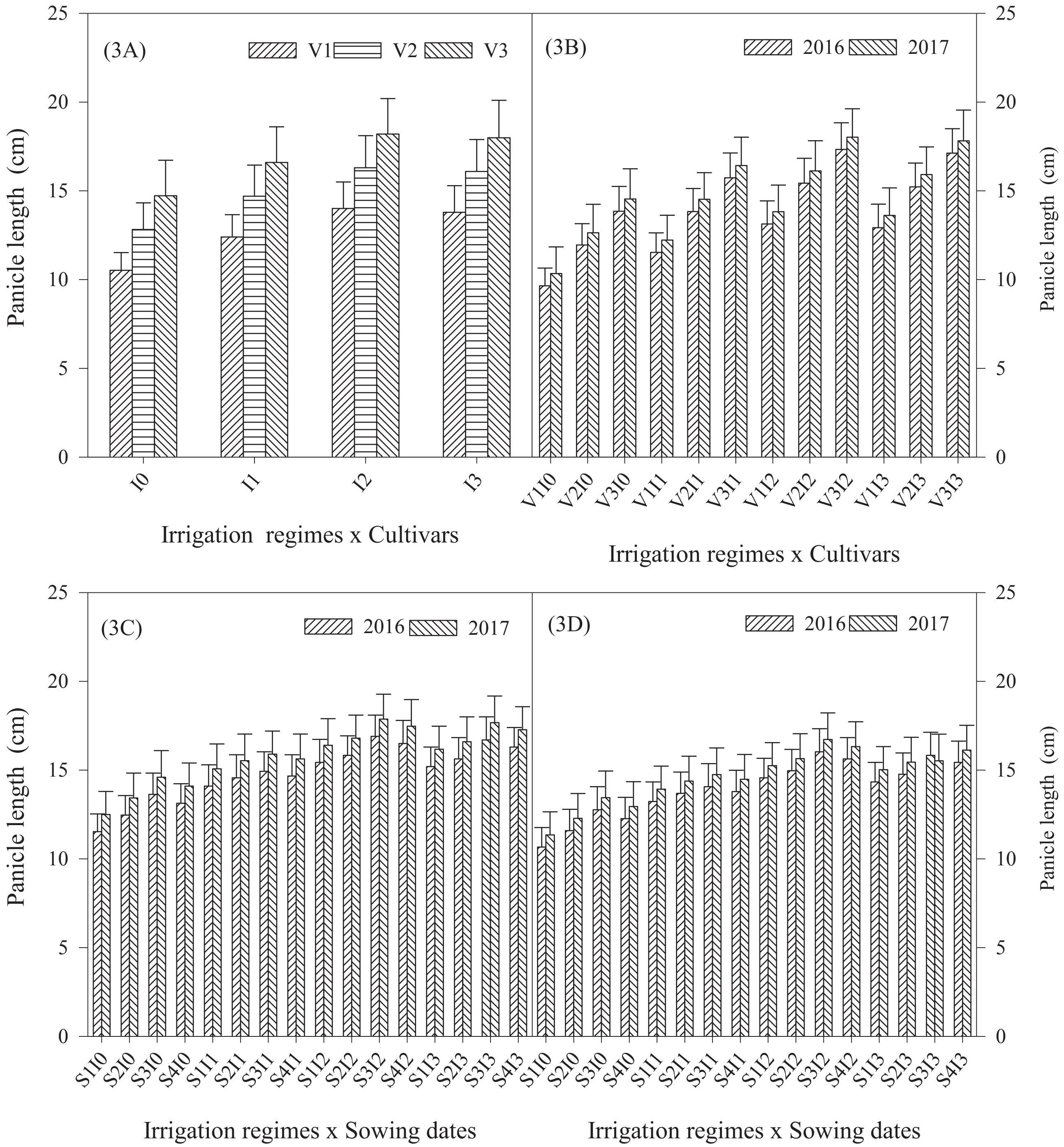

Figure 3. Interactive effect of irrigation regimes and sorghum cultivars at Sahiwal during 2016 (A), irrigation regimes and sorghum cultivars at Multan during both years (B), irrigation regimes and sowing dates at Sahiwal during both years, and (C) irrigation regimes and sowing dates at Multan during both years on panicle length. Bars represent SE.

were attained for SD_3 (15 July) followed by SD_4, followed by SD_2. The lowest seed productivity, biological yield, and HI were observed for S_1 (15 June) at both locations in 2016 and 2017. Concerning irrigation regimes, the highest seed productivity, biological yield, and HI observed at Sahiwal (3306.49 and 3351.39 kg ha^{-1}; 26495 and 26694 kg ha^{-1}; 49.67 and 50.51%) were observed for six irrigations (I_2), followed by I_3, which were statistically at par in 2016 and 2017. A similar tendency was also recorded at Multan, where the highest seed productivity, biological yield, and

Table 3. Impact of different irrigation regimes and sowing dates on the stem diameter &1000-seed weight (g) of various sorghum cultivars.

Experimental Treatments	Stem Diameter (cm)				1000-seed weight (g)			
	Sahiwal		Multan		Sahiwal		Multan	
Irrigation Levels (I)	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
I_0 = 2 Irrigation	0.65 B	0.77 B	0.60 C	0.62 C	21.23 C	21.27 C	21.21 D	21.23 C
I_1 = 4Irrigation	0.83 B	0.85 B	0.78 B	0.81 B	21.87 B	21.89 B	21.83 C	21.88 B
I_2 = 6Irrigation	1.37 A	1.42 A	1.30 A	1.33 A	23.11 A	23.14 A	23.08 A	23.10 A
I_3 = 8Irrigation	1.25 A	1.32 A	1.23 A	1.26 A	22.99 A	22.93 A	22.89 B	22.90 A
LSD (I) ($p \leq 0.05$)	**0.23**	**0.12**	**0.10**	**0.13**	**0.14**	**0.21**	**0.20**	**0.22**
Sorghum Varieties (V)								
V_1 = YSS 98	0.96 C	1.01 C	0.91 C	0.94 C	22.20 B	22.25 B	22.15 B	22.17 C
V_2 = Y 16	1.00 B	1.07 B	0.97 B	0.99 B	22.25 B	22.30 B	22.22 B	22.25 B
V_3 = Lasani hybrid	1.10 A	1.14 A	1.04 A	1.08 A	22.37 A	22.39 A	22.34 A	22.36 A
LSD (V) ($p \leq 0.05$)	**0.03**	**0.03**	**0.05**	**0.04**	**0.07**	**0.08**	**0.06**	**0.05**
Sowing Dates (SD)								
S_1 = 15th June	0.84 D	0.90 D	0.79 D	0.87 D	21.88 D	21.91 D	21.84 D	21.85 D
S_2 = 1st July	0.96 C	1.01 C	0.93 C	0.99 C	22.15 C	22.19 C	22.12 C	22.13 C
S_3 = 15th July	1.19 A	1.21 A	1.16 A	1.17 A	22.63 A	22.66 A	22.58 A	22.61 A
S_4 = 30th July	1.08 B	1.17 B	1.02 B	1.07 B	22.46 B	22.48 B	22.41 B	22.44 B
LSD (SD) ($p \leq 0.05$)	**0.07**	**0.02**	**0.10**	**0.06**	**0.04**	**0.05**	**0.05**	**0.09**
Significance Level (I)	**	**	**	**	**	**	**	**
Significance Level (V)	**	**	**	**	**	**	**	**
Significance Level (I × V)	**	**	**	**	NS	NS	NS	NS
Significance Level (SD)	**	**	**	**	**	**	**	**
Significance Level (I × SD)	**	**	**	**	**	**	**	**
Significance Level (V × SD)	NS	NS	NS	NS	NS	NS	NS	NS
Significance Level (I × V × SD)	NS	NS	NS	NS	NS	NS	NS	NS

Note: Any two means followed by same letter are not significantly different; n = 3. NS = nonsignificant; ** = significant at $p \leq 0.01$

HI (3256.71 and 3289.45 kg ha^{-1}; 26275 and 26384 kg ha^{-1}; 47.98 and 48.76%) were attained for I_2, followed by I_3 which were statistically at par in 2016 and 2017. Regarding irrigation regimes, the lowest seed productivity, biological yield, and HI was observed for I_0 at Sahiwal and Multan in 2016 and 2017. The interactive effects I × V and I × SD for higher seed productivity, biological yield, and HI were observed for the Lasani hybrid planted on 15 July with I_2 (Figures 6, 7). A superior result for all productivity attributes was observed at Sahiwal. Increasing trends for the studied attributes were recorded in 2017 compared with 2016. For both years at Sahiwal and Multan, decreasing trends for productivity attributes were I_2>I_3>I_1 >I_0 for irrigation regimes, V_3> V_2> V_1 for cultivars, and SD_3> SD_4> SD_2> SD_1 for sowing dates.

4. Discussion

This study's findings illustrate that all the individual variables analyzed (planting dates, irrigation levels, and sorghum varieties) substantially impacted the studied attributes. Crop production is significantly affected by the availability and quality of irrigation water, the time and amount of water applied, and the water supply. Improving reliability can improve irrigation timing and establish proper sowing time and proper selection of varieties, promoting crop growth and improving productivity. Higher values of grain yield and attributes were recorded at Sahiwal than at Multan. This result may be attributed to the higher rainfall in total at Sahiwal, or almost 2 °C higher minimum temperature at Multan. Furthermore, more sunshine hours were recorded at Sahiwal, which

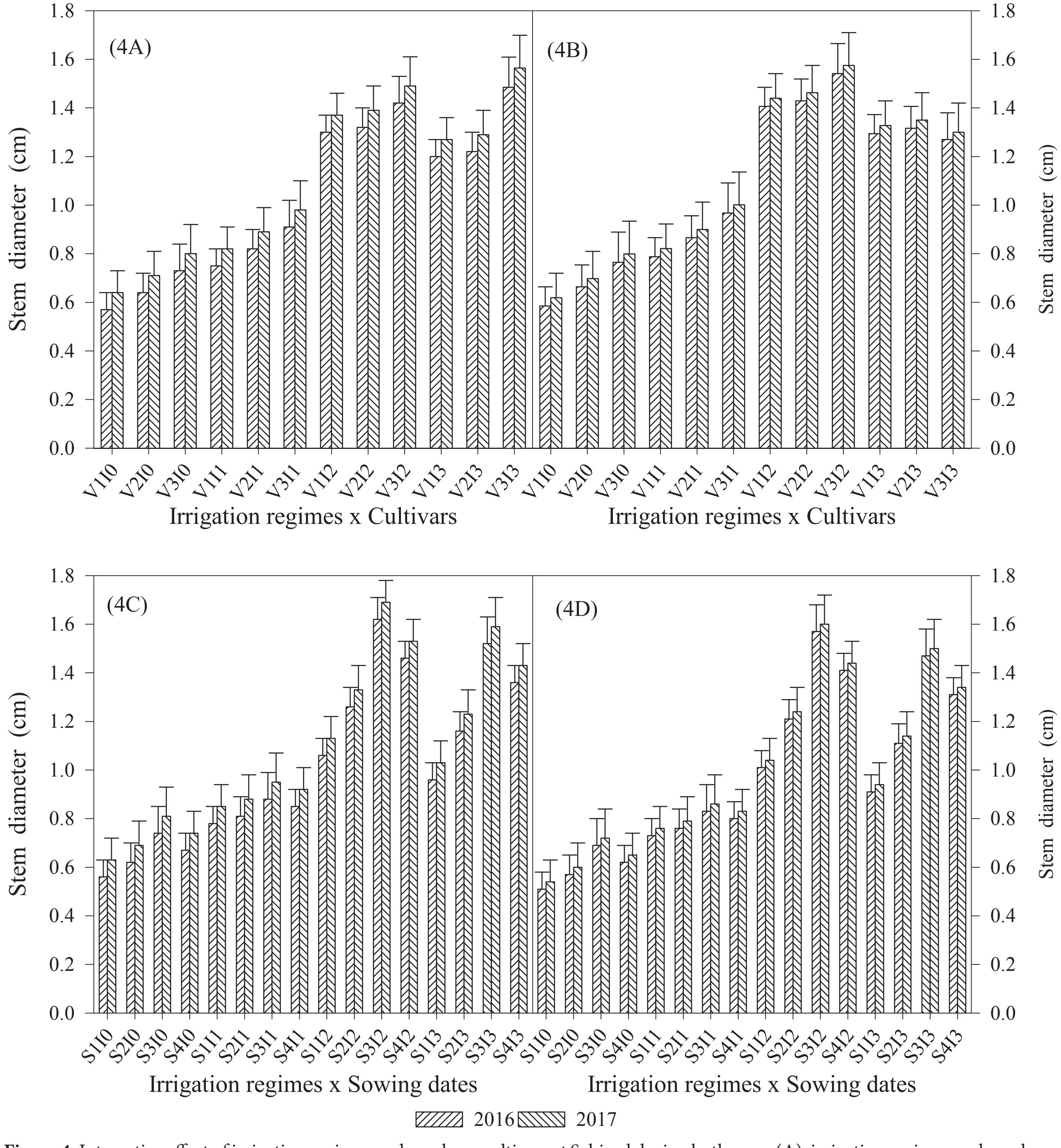

Figure 4. Interactive effect of irrigation regimes and sorghum cultivars at Sahiwal during both years (A), irrigation regimes and sorghum cultivars at Multan during both years (B), irrigation regimes and sowing dates at Sahiwal during both years, and (C) irrigation regimes and sowing dates at Multan during both years (D) on stem diameter. Bars represent SE.

may have resulted in more photo-assimilation and more radiation use efficiency and ultimately higher grain yield. At both study locations, higher values of grain yield and its components were recorded in 2017 than in 2016, which may be the outcome of climatic conditions. The rainfall was uniformly distributed during the second year, which resulted in more leaf area, head length, stem diameter, 1000-grain weight, and grain yield (Mubarik, 2021).

Concerning sowing dates, the highest grain yield and components were attained for the 15 July sowing date (SD_3) at both locations, which may have resulted from optimum climatic conditions. For earlier sowing

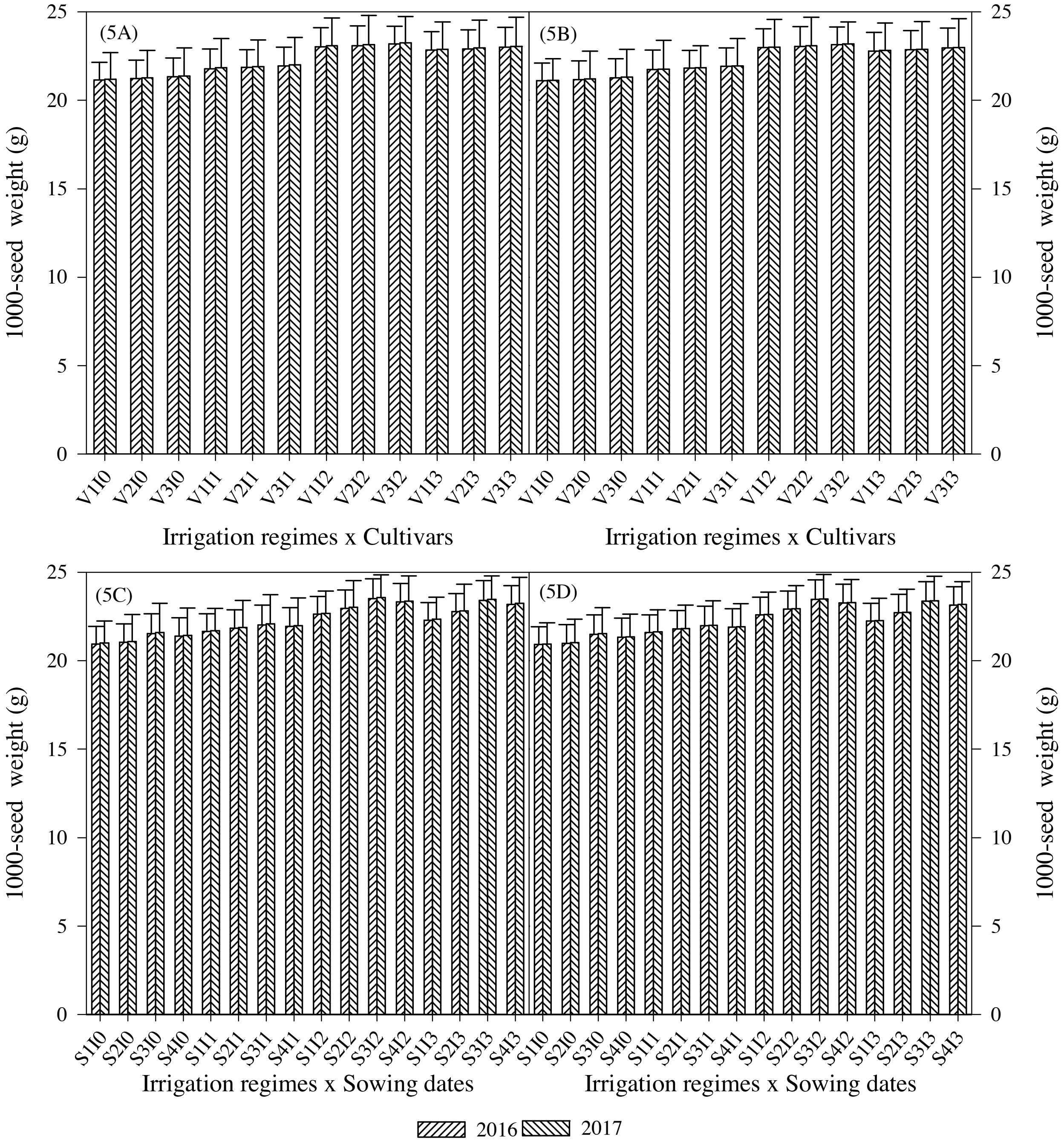

Figure 5. Interactive effect of irrigation regimes and sorghum cultivars at Sahiwal during both years (A), irrigation regimes and sorghum cultivars at Multan during both years (B), irrigation regimes and sowing dates at Sahiwal during both years, and (C) irrigation regimes and sowing dates at Multan during both years on 1000-seeds weight. Bars represent SE.

dates, the lower values of yield and its components may result from the interactive effect of higher maximum and minimum temperatures, which negatively affected the photosynthesis process, dry matter accumulation, and dry matter portioning for the sorghum crop. According to Mubarik (2021), appropriate growing degree days are obtained by sowing the sorghum crop on optimum sowing dates. The sowing time of a particular suitable cultivar in specific climate conditions significantly impacted physiological processes, and ultimately the grain yield and components of a cultivar under consideration (Rezazadeh et al., 2019). An appropriate planting date for the sorghum varieties is critical for the expression of their growth and development patterns to their fullest extent in a diverse set

Table 4. Impact of different irrigation regimes and sowing dates on the seed yield & biological yield (kg/ha) of various sorghum cultivars.

Experimental Treatments	Seed Yield (kg/ha)				Biological Yield (kg/ha)			
	Sahiwal		Multan		Sahiwal		Multan	
Irrigation Levels (I)	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**	**2016**	**2017**
I_0 = 2 Irrigation	1963.38 D	2031.15 D	1924.65 D	1939.27 D	19135 D	19404 D	18955 D	19144 D
I_1 = 4Irrigation	2829.43 C	2879.33 C	2759.78 C	2812.48 C	21918 C	22257 C	21768 C	21877 C
I_2 = 6Irrigation	3306.49 A	3351.39 A	3256.71 A	3289.45 A	26495 A	26694 A	26275 A	26384 A
I_3 = 8Irrigation	3285.61 A	3339.47 A	3215.99 B	3253.51 A	25761 A	25930 A	25271 B	25593 A
LSD (I) ($p \leq 0.05$)	**24.31**	**21.98**	**19.56**	**34.89**	**700.15**	**783.56**	**653.98**	**795.89**
Sorghum Varieties (V)								
V_1 = YSS 98	2734.09 C	2771.91 C	2685.98 C	2716.96 C	22402 C	22534 C	22201 C	22379 C
V_2 = Y 16	2832.70 B	2877.78 B	2776.98 B	2802.45 B	23197 B	23432 B	22977 B	23106 B
V_3 = Lasani hybrid	2941.91 A	2981.45 A	2902.20 A	2934.21 A	24077 A	24275 A	23875 A	24106 A
LSD (V) ($p \leq 0.05$)	**72.34**	**68.78**	**54.98**	**59.87**	**542.89**	**658.89**	**615.45**	**496.78**
Sowing Dates (SD)								
S_1 = 15th June	2604.39 D	2621.24 D	2564.75 D	2591.35 D	21613 D	21912 D	21404 D	21592 D
S_2 = 1st July	2800.84 C	2832.71 C	2761.13 C	2790.81 C	22485 C	22704 C	22286 C	22404 C
S_3 = 15th July	3034.78 A	3056.63 A	2995.08 A	3021.70 A	25232 A	25441 A	25098 A	25211 A
S_4 = 30th July	2989.67 B	3003.07 B	2865.10 B	2891.87 B	23688 B	23877 B	23408 B	23607 B
LSD (SD) ($p \leq 0.05$)	**12.45**	**11.89**	**15.89**	**21.67**	**276.39**	**357.56**	**215.89**	**410.78**
Significance Level (I)	**	**	**	**	**	**	**	**
Significance Level (V)	**	**	**	**	**	**	**	**
Significance Level (I × V)	**	*	**	**	**	*	**	NS
Significance Level (SD)	**	**	**	**	**	**	**	**
Significance Level (I × SD)	**	**	**	**	**	**	**	**
Significance Level (V × SD)	NS	NS	NS	NS	NS	NS	NS	NS
Significance Level (I × V × SD)	NS	NS	NS	NS	NS	NS	NS	NS

Note: Any two means followed by same letter are not significantly different; n = 3. NS = nonsignificant; ** = significant at $p \leq 0.01$

of environmental dynamics. For the farming community, determining the optimum sowing date for cultivars under particular environmental conditions is vital to maximizing grain production (Zander et al., 2021). The sowing date is an essential factor in successful sorghum production; hence, sowing too early or too late has resulted in lower yields (Chitte et al., 2008). In this study, the highest sorghum yield was obtained by applying six irrigations (I_2); however, this result was statistically at par with eight irrigations (I_3) at both locations for 2016 and 2017. Applying an excess or too little water instead of the optimum amount resulted in poor growth, smaller leaf area, a lower net assimilation rate, and lower radiation use efficiency, and lower uptake of solutes from the soil resulted in lower grain yield and components. Although sorghum crop production exhibits tolerance to drought, its vegetative and reproductive growth stages during crop growth periods were negatively affected by a lower irrigation application. Nevertheless, according to Mubarik's (2021) findings, a higher irrigation level did not result in a significant increase in yield and yield-related parameters. Taiz and Zeiger (2006) observed that water stress significantly impacts internodal length, stalk weight, head length, and plant height, all of which affect crop yield. Both the timing and severity of stress affect sorghum yield and yield-related attributes, according to Craufurd and Peacock (1992). Craufurd and Peacock (1992) found that stress applied during flowering and booting (late stress) resulted in the most significant reduction in grain yield; however, the same stress treatment on vegetative plants had no impact on yield during early flowering. An increase in the timeframe of extreme stress on vegetative phases decreased productivity. Gudu et al. (2007) indicated that water stress in sorghum resulted in a decrease in the number of leaves and plant height. Low

Table 5. Impact of different irrigation regimes and sowing dates on the harvest index (%) of various sorghum cultivars.

Experimental Treatments	**Harvest Index (%)**			
	Sahiwal		**Multan**	
Irrigation Levels (I)	**2016**	**2017**	**2016**	**2017**
I_0 = 2 Irrigation	10.26 D	10.47 D	10.15 D	10.12 D
I_1 = 4Irrigation	12.91 A	12.93 A	12.68 B	12.85 A”
I_2 = 6Irrigation	12.48 C	12.55 C	12.39 C	12.47 C
I_3 = 8Irrigation	1 2.75 B	12.87 B	12.73 A	12.71 B
LSD (I) ($p \leq 0.05$)	**0.11**	**0.05**	**0.04**	**0.12**
Sorghum Varieties (V)				
V_1 = YSS 98	12.18 D	12.30 A	12.11 B	12.14 B
V_2 = Y 16	12.21 B	12.28 C	12.08 C	12.12 C
V_3 = Lasani hybrid	12.23 A	12.28 A	12.16 A	12.17 A
LSD (V) ($p \leq 0.05$)	**0.01**	**0.01**	**0.02**	**0.03**
Sowing Dates (SD)				
S_1 = 15th June	12.05 C	11.96 C	11.98 C	12.00 C
S_2 = 1st July	12.45 B	12.71 A	12.39 A	12.46 A
S_3 = 15th July	12.03 C	12.01 C	11.93 C	11.99 C
S_4 = 30th July	12.63 A	12.58 B	12.24 B	12.25 B
LSD (SD) ($p \leq 0.05$)	**0.15**	**0.12**	**0.11**	**0.18**
Significance Level (I)	**	**	**	**
Significance Level (V)	**	**	**	**
Significance Level (I × V)	*	**	NS	*
Significance Level (SD)	**	**	**	**
Significance Level (I × SD)	**	**	**	**
Significance Level (V × SD)	NS	NS	NS	NS
Significance Level (I × V × SD)	NS	NS	NS	NS

Note: Any two means followed by same letter are not significantly different; n = 3. NS = nonsignificant; ** = significant at $p \leq 0.01$

development due to reduced photosynthetic capability may explain the decrease in these parameters. This result was expected because photosynthesis, which requires water, is the primary cause of the plant's growth and accumulation of dry matter. A crop's physiological response to a water deficit involves leaf rolling, reducing the leaf area, which directly interferes with the photosynthesis carbon dioxide uptake. As a result, a lack of water in the soil will limit overall plant development (Sanchez et al., 2002). In this study, it was observed that during vegetative growth, water stress reduced plant height. Water applied at the start of vegetative production greatly improved plant growth, and the effect could be seen a few days later. Water stress during reproduction can lead to premature loss of leaves and reduced grain and dry matter yield due to reduced radiation interception. In the sensitive phase in arid years, single irrigation can lead to yield loss of 30%–40%. A more significant water deficit is likely to cause much of the loss in grain yield (Cakir, 2004).

The sorghum cultivar Lasani hybrid produced higher grain yield and components than YSS 98 and Y 16. The reason may be the higher leaf area of the Lasani hybrid and its better adaptability to environmental conditions than other cultivars. Higher photo-assimilates were produced due to more leaf area. During the period of the most rapid dry matter accumulation, the quantity of total dry matter accumulated per sorghum plant was proportional to the leaf area of the cultivar. A higher net assimilation rate for the Lasani hybrid was due to a more erect flag leaf. The Lasani hybrid leaves' photosynthetic efficiency resulted

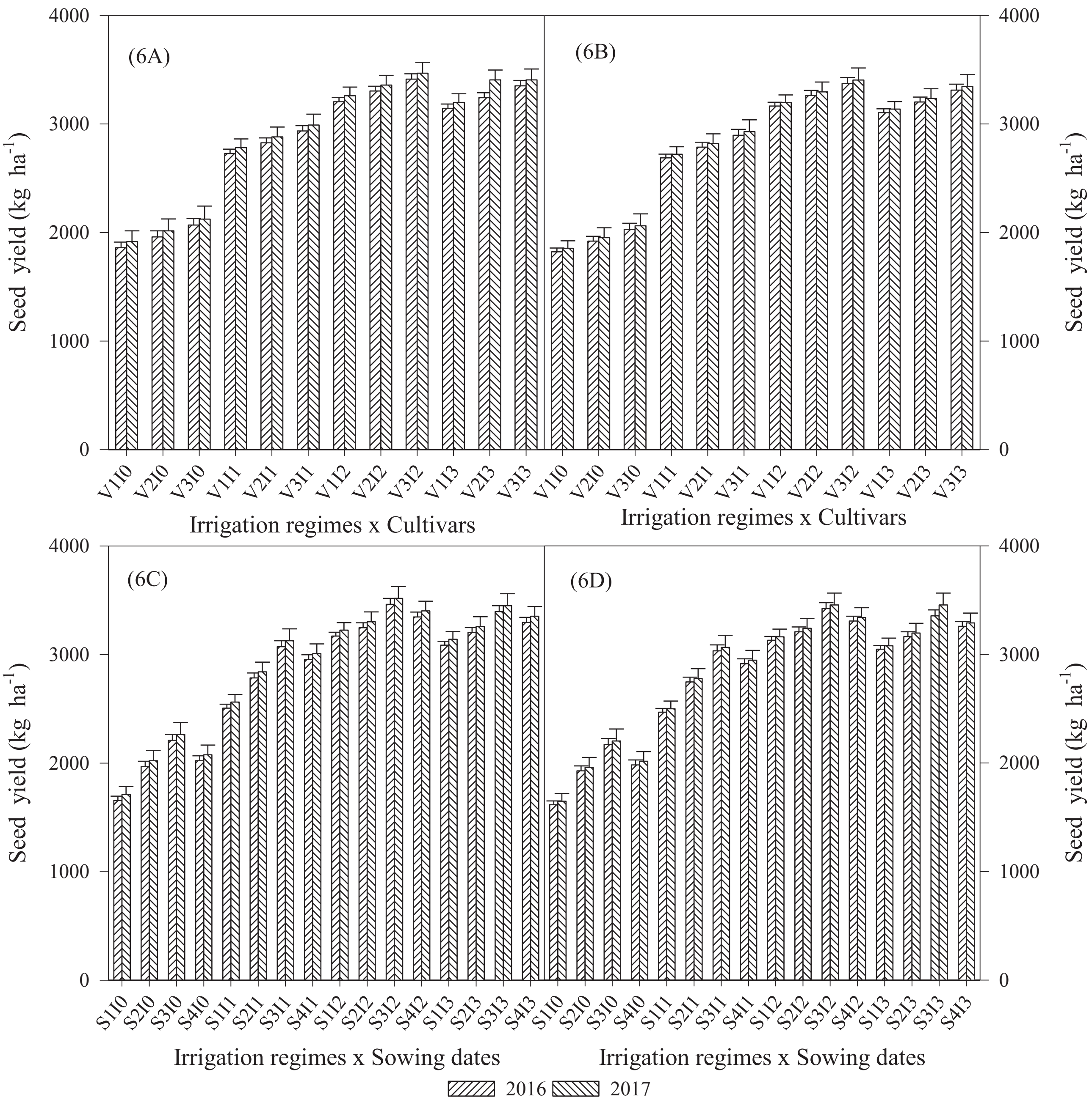

Figure 6. Interactive effect of irrigation regimes and sorghum cultivars at Sahiwal during both years (A), irrigation regimes and sorghum cultivars at Multan during both years (B), irrigation regimes and sowing dates at Sahiwal during both years, and (C) irrigation regimes and sowing dates at Multan during both years (D) on seed yield. Bars represent SE.

in greater dry matter production than for other cultivars. In addition, the Lasani hybrid produced more tillers, so a greater number of grains and heads resulted in higher grain production (Mubarik, 2021). The characteristics of the vegetative and reproductive stages of the Lasani hybrid may be the cause of increased yield under favourable environmental conditions. This effect could be attributed to a general improvement in plant growth, as evidenced by the increase in the crop's flag leaf area. During the reproductive stage of the plant, early harvesting's significant increase in all yield attributes may be attributed to better nutrient uptake and photosynthesis translocation resulting in smaller grains. The results of this research are consistent with the findings of Narwal et al. (2005) and Raei and Sharifi (2009). Higher grain yield may be due to a higher quantity of leaves per plant in sorghum cultivars. The leaf

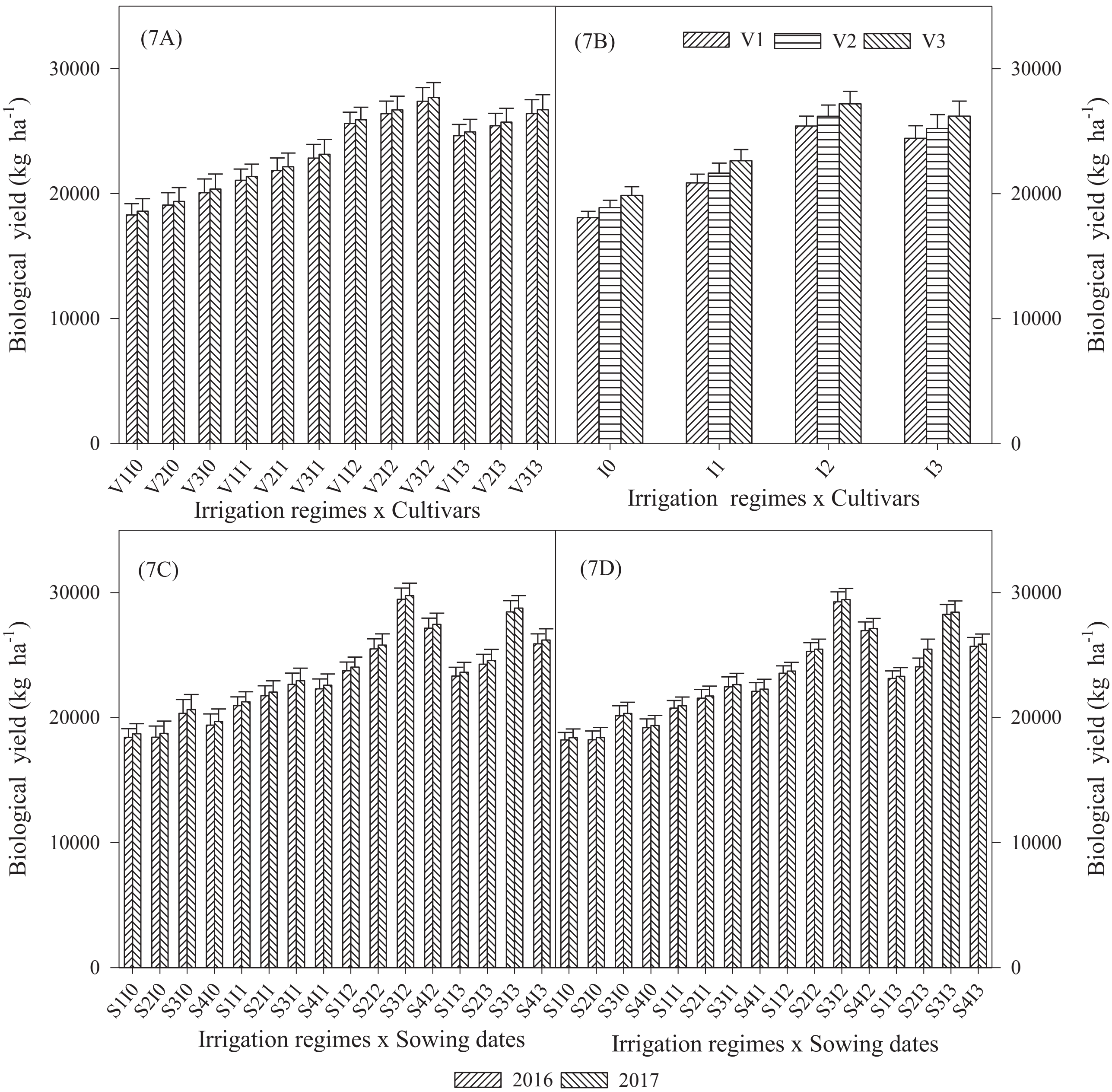

Figure 7. Interactive effect of irrigation regimes and sorghum cultivars at Sahiwal during both years (A), irrigation regimes and sorghum cultivars at Multan during 2016 (B), irrigation regimes and sowing dates at Sahiwal during both years, and (C) irrigation regimes and sowing dates at Multan during both years on biological yield. Bars represent SE.

characteristics differed according to genotype and sowing dates. Hotsonyame and Hunt (1997) stated that genotypes and planting dates significantly affect the flag leaf area. Irrigation, photoperiod, nutrients and temperature influence changes in the cultivar leaf area (Tardieu et al., 2005). Khalil et al. (2002) observed a connection between leaf area and planting dates and found that the leaf area of genotypes has decreased when planting is delayed.

It may be verified by nonideal conditions of a seedbed, which allows for a lower incidence of germination compared with the laboratory's ideal situation for optimum germination rate (Makkawi et al., 1999). This study's results are consistent with the conclusion by Khan et al. (2010) showing that there is an important relationship between sowing time and field development. Regarding sowing dates, the results of this study illustrate that the field potential of seed samples for both variables was statistically significant. Crop growth steadily declines due to delayed planting. Temperature changes in the late sowing period affect seed germination and cause poor crop development, affecting plant population (Abbas et al., 2017). Scientists have found that temperature changes lead to poor and irregular plant growth and development (Timmermans et al., 2007). Tahir et al. (2009) concluded that the sowing time has a significant impact on the growth characteristics of different wheat varieties.

It has been found that plant heights vary significantly due to several practices, such as planting dates, irrigation levels, and the choice of plant variety. The results of this study are consistent with the findings of Farooq et al. (2008), which found a significant correlation between plant height and sowing time. The genetic diversity of cultivars may be the cause of a difference in plant height (Shah et al., 2006), whereas varietal and sowing date effects may be the cause of contrary outcomes (Tahir et al., 2009). Delayed sowing resulted in a significant decrease in plant height. This effect may be due to rapid changes in the photoperiod, which accelerate development to the reproductive stage and reduce the time for vegetative growth. When planting is late, temperature fluctuations also reduce plant height (Shehzad et al., 2002). Shah (2001) found that compared with irrigated crops, unirrigated plants are under stress throughout the year due to the significant reduction in plant height. However, the results are inconsistent with other studies. Khan et al. (2003) found inconsistent results among different irrigation rates. When water stress was applied, the number of leaflets and plant height decreased, indicating that water stress affected plant development.

Early sown crops have a longer growth cycle from planting to maturity. As a result, plants' growth rate, photosynthesis production and distribution to reproductive streams are higher than for later sown crops. These results were also obtained by Qasim et al. (2008) and Sattar et al. (2010), which found that plants sown earlier have better yield traits. The difference in yield characteristics between varieties may be related to the genetic variation of sorghum and maize diversity may be a cause (Haider, 2004). Approximately one-half of the flowers were dropped prior to blooming, and others were not fully developed, which reduced the yield.

Higher biological yields from early sown plants may be related to longer seed maturity growth, which means that the plant growth period can be prolonged, ultimately leading to higher biological yield. According to the findings of Wang et al. (2004), the differences in biomass productivity among varieties may be related to genetic composition because physiological attributes determine biomass yield. These results are inconsistent with the outcomes of Sattar et al. (2010). Sattar et al. (2010) concluded that there are higher biological yields from early sown plants possibly related to longer seed maturity growth, which means that plant growth can be prolonged, ultimately leading to higher biological yield.

Crop yields are depressed due to delayed sowing, resulting in poor crop development, as Filho and Ellis (2008) described. In early planted crops, the peak flag leaf area, head length, and grain weight contributed to higher yields. As a result, the optimal sowing time is critical to obtain a higher grain yield. Hussein et al. (1998) also found that delayed wheat planting may be the reason for the reduction of 36 kg ha^{-1} day^{-1}. These results were consistent with several earlier studies, such as Akhtar (2006), who reported that late sowing significantly reduced grain yields.

The genetic make-up of cultivars also influences variability in yield. Dokuyucu et al. (2004) reported similar considerations and illustrated that later planting significantly affects grain filling. Scientists compared the effect of early and late sowing on the production of higher grain weight (Singh and Pal, 2003; Abdullah et al., 2007; Abbas et al., 2017). There was significant variance in yield characteristics between sowing dates and cultivar interactions. Early sowing dates yielded better results than late sowing dates for all cultivars. The difference in percentage of all varieties was greatest at the first sowing date and lowest at the last sowing date. This result may be related to the different reactions to photoperiod and temperature fluctuations in the plants, and size and weight discrepancies in the seed and the ripening unit. Quantity and distribution of precipitation, changes in temperature, and short photoperiod can all contribute to the reduction of flag leaf area in delayed planting. Under early and late sowing conditions, all cultivars showed variation in the flag leaf field (Nataraja et al., 2006).

Early planting and high grain yields are likely to be attributed to the success of using environmental variables. Compared with later planting, early planting environmental variables help accumulate dry matter faster and lower yields. This result may be due to shorter growing seasons and daytime temperatures for later planting dates. Higher and lower soil moisture content and humidity during the reproductive phase lead to decreased yield. Photosynthesis, disease incidence, stemmatological resistance, decreased photosynthetic efficiency of the crop, and water effectiveness are all indirectly influenced by the direct impact of relative humidity on the plant's water relationship (Kumar et al., 2008). As a result, crops grown in the most favourable climate conditions would have a high photosynthetic production (Wani et al., 2002; Rao et al., 2004). Wani et al. (2002) and Rao et al. (2004) found that when the genotype was sown on 15 July, the stem weight, 1000-seed weight, productivity, and biomass production were statistically higher. The positive impact of sowing time on yield indicators may be related to the significant increase in the early harvest. This result leads to increased plant height and dry matter accumulation, leading to higher yields (Dixit et al., 2005; Chitte et al., 2008). Narayanan (2007) concluded that sorghum loses its physiological activity under water scarcity during the vegetative phase (before flowering) without significantly reducing the yield. The water stress in the early stage of grain sorghum has a much greater inhibitory effect on grain yield than in other phases and stages (Abbas et al., 2020; Ahmad et al., 2012, 2015; Fatima et al., 2018). After flowering, stress shortens the period of grain filling, which reduces the size and seed number and leads to reduced yield or even a complete crop failure (Mkhabela, 1995; Naz et al., 2022).

5. Conclusion

Increased water stresses during phenological stages and phases lead to a significant decrease in sorghum's grain yield and productivity traits and may show phenotypic plasticity. These benefits allow farmers to reap optimum yield. Furthermore, the stability of local cultivars and their use in breeding programs could have a significant role in productivity improvement.

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