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RESEARCH ARTICLE

Conformance of sowing dates for maximizing heat use efficiency and seed cotton yield in arid to semi-arid cotton zone of Pakistan

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Abstract

Pakistan is placed among the most vulnerable countries with relation to climate change and its impacts on agricultural productivity. Cotton is staged as the cash crop of the country and the main source of raw material for textile, oil, and feed industry. Varying environmental attributes have significant effects on the duration of vegetative and reproductive stages of cotton crop. To evaluate the potential impacts of varied temperatures regimes in different sowing times, field experiments were carried out throughout the cotton growing areas of Pakistan from Faisalabad in Central Punjab to RYK in Southern Punjab and Sakrand in Sindh to Dera Ismail Khan in Khyber Pakhtunkhwa (KPK) Province. Crop was sown on six different sowing dates starting from 1st March towards 15th May with 2-week intervals for two crop seasons (2016 and 2017). The timing of phenological events like emergence, squaring, flowering, and boll opening was recorded on calendar days and cumulative heat units (GDDs) were calculated for flowering and boll opening stages. Heat use efficiency for these sowing times was estimated. Data regarding yield-related parameters like opened bolls per plant, average boll weight, and seed cotton yield were also recorded during the study. Results revealed that duration of the growth stages was significantly affected by variation in mean thermal kinetics in varied sowing times in all four different environments. Seed cotton yield and heat use efficiency were also varied among the locations and sowing dates. The maximum seed cotton yield was recorded in Sakrand location at 15th April sowing date. The dependence of the phenological advancement on temperature and negative impacts of higher thermal stress on cotton productivity were also confirmed throughout the cotton growing zone of Pakistan.

Keywords Cotton (*Gossypium hirsutum* L.) · Environment · Temperature · Phenology · Heat units · Fiber · Seed cotton yield

Introduction

Cotton (*Gossypium hirsutum* L.) is grown throughout the world as a major fiber crop (Buttar et al. 2013; Ahmad et al. 2017) and is cash crop of Pakistan (GOP 2020). Its fiber is an important input for the whole textile sector globally (ICAC 2019). The crop life-sustaining processes like photosynthesis and respiration depend upon environmental factors like ambient temperature, solar radiation, and precipitation along with soil and crop management attributes (Luo 2011; Gonias et al. 2012). Although cotton crop is successfully grown in tropics and subtropics, yet it is mostly affected negatively by heat stress during flowering and boll formation period resulting in lower boll weight and crop yields (Iqbal et al. 2017; Mahday et al. 2017). Abrupt changes in weather elements during recent years, resulting in less water availability at important crop development stages and higher pest pressure are the major reasons of lower cotton yield (GOP 2020).

Phenology is defined as the scientific study of periodic plant life cycle events starting from germination to development of fruiting bodies through floral initiation and how these events have been associated with seasonal and inter-annual climatic variations (Zhao et al. 2013). Temperature is very basic necessity of plant life as it not only contributes towards plant biomass production and its partitioning into various plant parts but also affects phenology at large (Sankarnarayanan et al. 2010). Crop growth, development and yields have been affected by only temperature out of

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many environmental factors (Luo 2011). Cotton requires a minimum temperature range of 12–15 °C to start physiological activities, reaching at optimal level at temperature of 26–28 °C while the effect of maximum temperature depends on its exposure frequency (Reddy et al. 1997). The optimal thermal kinetic window for efficient cotton metabolic activities is considered between 23 and 32 °C (Burke et al. 1988; Conaty et al. 2012). Every genotype interacts with its environment variably during key periods of planting to square initiation and flowering to start of boll opening (Reddy et al. 1997). In adoption of new improved crop cultivars, managing sowing time can be a solution to cope this harmful impact on crop phenology (Liu et al. 2006; Singh et al. 2007; Wolkovich et al. 2012). In Pakistan, where climatic conditions are largely varied among different agro-ecological zones, sowing time is considered vital for getting superior seed cotton yield on sustainable basis in all cotton growing zone of the country (Ali et al. 2009; Deho et al. 2012). As, the modified planting time at any site, is a way to avoid the thermal stress during crop growth and development.

It is obligatory to look into the numerical interactions between plant and its environment to explain their effects on reproductive stage of the plant (Sadras et al. 1997). Growing degree day (GDD) models have a potential to display crop development and forecast phenology of cotton (Reddy et al. 1992). The duration of each crop developmental phase defines accumulation as well as partitioning of total dry matter into different plant parts along with crop responses towards varying environmental attributes (Dalton 1967). In literature, calculation of GDDs have been made with the base temperature ranging from 12 °C (Constable and Shaw 1988) to around 15 °C (Robertson et al. 2007).

Hence, in order to get the maximum cotton yield, it is a dire need to investigate the effect of sowing time on phenology, GDDs turn over and cotton yield at different locations. Keeping this in view, the present study was planned to explore the effect of differential temperatures at varied environmental locations on cotton phenology, GDD accumulation at various phenophases, seed cotton yield, and heat use efficiency in cotton cultivar FH 142 grown with the gap of 15 days from early-March to mid-May.

Materials and methods

Experimental sites description

Field experiments for two consecutive years (2016 & 2017) were conducted at Research Area of Department of Agronomy, University of Agriculture, Faisalabad. Faisalabad was considered as a house of cotton during 60s and most of the textile industry is located in this city. This city lies in the center of the country with dry semi-arid climate having rainfall about 350 mm, annually. The soil of the experimental site is Aridisol, mixed, hyperthermic Ustalfic, Haplagrid, and Haplic Yermosol according to soil taxonomy, Soil Survey Staff and FAO-UNESCO, respectively (Rahman et al. 2017). The major crops grown in the area are maize, wheat, sugarcane, rice, and cotton along with orchards of guava and orange mainly with the help of canal irrigation water.

The 2nd experimental site was Cotton Research Station (CRS) Khanpur, Rahim Yar Khan, the southern side of the Punjab Province. The area is known for cash crops comprising of high quality cotton and sugarcane. The climate of the region is also considered as dry semi-arid with annual rainfall of about 270 mm. The soil of the region is classified as Fine, mixed, hyperthermic, and Fluventic Haplocambids. The main crops include cotton and rice in *Kharif* season while wheat in *Rabi* season along with sugarcane as a single annual crop.

The 3rd experimental site was Central Cotton Research Institute, (CCRI) Sakrand, located in central Sindh in district Shaheed Benazir Abad formerly known as Nawabshah, the heart of Sindh Province. The major crops in this district are wheat, cotton and sugarcane along with orchards of world famous mango and banana. The climate of the area is considered as dry arid because very few rainfall (about 36 mm) occurs annually in this part of the country. The soil of area is fine silty, mixed, hyperthermic, and vertic torrifluvents as classified by Soil Survey of Pakistan and FAO-UNESCO.

The 4th experimental location was Cotton Research Station (CRS), Dera Ismail Khan (D I Khan), located on the southern border of Khyber Pakhtunkhwa Province. It is situated along the Suleman Pedamounts on the west bank of the River Indus. The major crop production of the area depends upon cotton, wheat, sorghum, and tobacco. The soil of the site is classified as Shahpur series (fine and mixed, haplocambids type and hyperthermic in nature) by Soil Survey of Pakistan and FAO-UNESCO.

Experimental layout

The Bt. cotton variety FH 142 was used as a test variety in the study. The experiment was laid out in randomized complete block design with split plot arrangement considering the four locations as main plot and 6 sowing dates in sub plots with three repeats of each experimental unit. The net plot size of 7 m × 4.5 m was maintained and the crop was sown on beds (75 cm apart) keeping plant to plant distance of 30 cm.

Crop husbandry

Fine seed beds were prepared by ploughing the field, cultivating twice and then final rotavating and planking operations during both years of experimentation. The experiments were sown according to the sowing treatments at all four locations. Nitrogen (N) at the rate of 125 kg per hectare (in the form of

Urea having 46 % N) was applied in three equal splits. One third of N and total phosphorus and potash (75 kg PK per hectare in the form of single super phosphate having 18 % P_2O_5 and Sulphate of Potash with 50% K_2O concentration, respectively) were broadcasted at the time of sowing while other two N splits were side dressed at squaring and peak flowering stages of the crop. All other agro-management practices like inter-culture, irrigation, and plant protection measures were managed uniformly in all the treatments.

Measurements

The plot area was divided equally in two halves and 1st half was utilized for observing phenological events and other growth indices like leaf area index and total dry matter production, while the remaining half was used to record final yield and other agronomic data at crop harvest.

Crop development

Randomly selected five plants were tagged from each plot for recording the occurrence of different phenophases like emergence, squaring, flower initiation, boll formation and opening. The experiments were visited during 9–11 am on daily basis and crop phenological observations for time to emergence, squaring, flowering and boll opening were recorded from each treatment.

Growing-degree-days/thermal time (Tt) for flower induction and boll opening period was determined as a function of mean temperature above base temperature (Tb = 12 °C) for each developmental phase as suggested by Gallagher et al. (1983)

$$Tt = \frac{\Sigma(Tmax + Tmin)}{2} - Tb$$

Heat use efficiency (HUE) for seed cotton yield and total dry matter was computed following Hundal et al. (2003).

$$HUE = Y/AHU$$

where Y is seed cotton yield or total dry matter, kg ha^{-1}, AHU= accumulated heat units, GDD

Final yield and ginning out turn at final harvest

For seed cotton yield, half of plot area (7 m × 2.25 m) from each treatment was manually picked which was converted into kg ha^{-1}. The ginning out turn (GOT) was estimated after the ginning of 100 g seed cotton from each plot using the formula:

$$\text{GOT }(\%) = \{(\text{lint weight/seed cotton weight}) \times 100\}$$

Meteorological data

Data regarding meteorological parameters of all four sites was gathered from the nearest Meteorological Observatories of Pakistan Meteorological Department located in Faisalabad, Rahim Yar Khan, Sakrand and D. I. Khan.

Statistical analysis

Fisher's analysis of variance technique was used for the analysis of data collected on various aspects including phenology and final cotton yield while honest significance difference (HSD) test at 5% probability level was used for testing the significance of treatment means (Steel et al. 1997). A computer based software (SAS V9.5) was used for Pearson Correlation and regression analysis.

Results

Weather parameters

The weather parameters were varied among the experimental locations during study period (Fig. 1). It is evident from the presented data that 2016 was cooler at early in the season than 2017 receiving more rainfall during this period of the year, whereas, there was less rainfall and higher thermal incidence during May–June in 2017. Among different locations, mean thermal range of 29.57 to 30.23 °C and rainfall amounting to 414.8 & 316.50 mm were received at Faisalabad during both years, respectively. The Khanpur site experienced maximum heat index during crop growing season (May–June) in comparison to other sites. The average temperature was ranging from 32.57 to 33.05 °C reaching to its maximum values in the months of June and May during both years of experiment, respectively. The rainfall in Khanpur was less than Faisalabad and D I Khan sites but it was higher than Sakrand, where it was minimum during both years of study. The 3rd experimental site, Sakrand, was confirmed as dry and hot site which gave the most favorable climatic indices for cotton productivity during the course of study. Dera Ismail Khan was mere cooler than other locations with the higher thermal range reaching to 41.89 °C during 2016 to 41.32 °C during 2017, respectively. The total rainfall during both crop growth seasons was also 281.70 and 178.49 mm, respectively.

Spatio-temporal variation and crop phenology

Time to emergence (days) The emergence of the crop is the first response towards crop establishment and is mainly impacted by soil characteristics and environmental attributes of the area. The analysis of the variance showed that time to

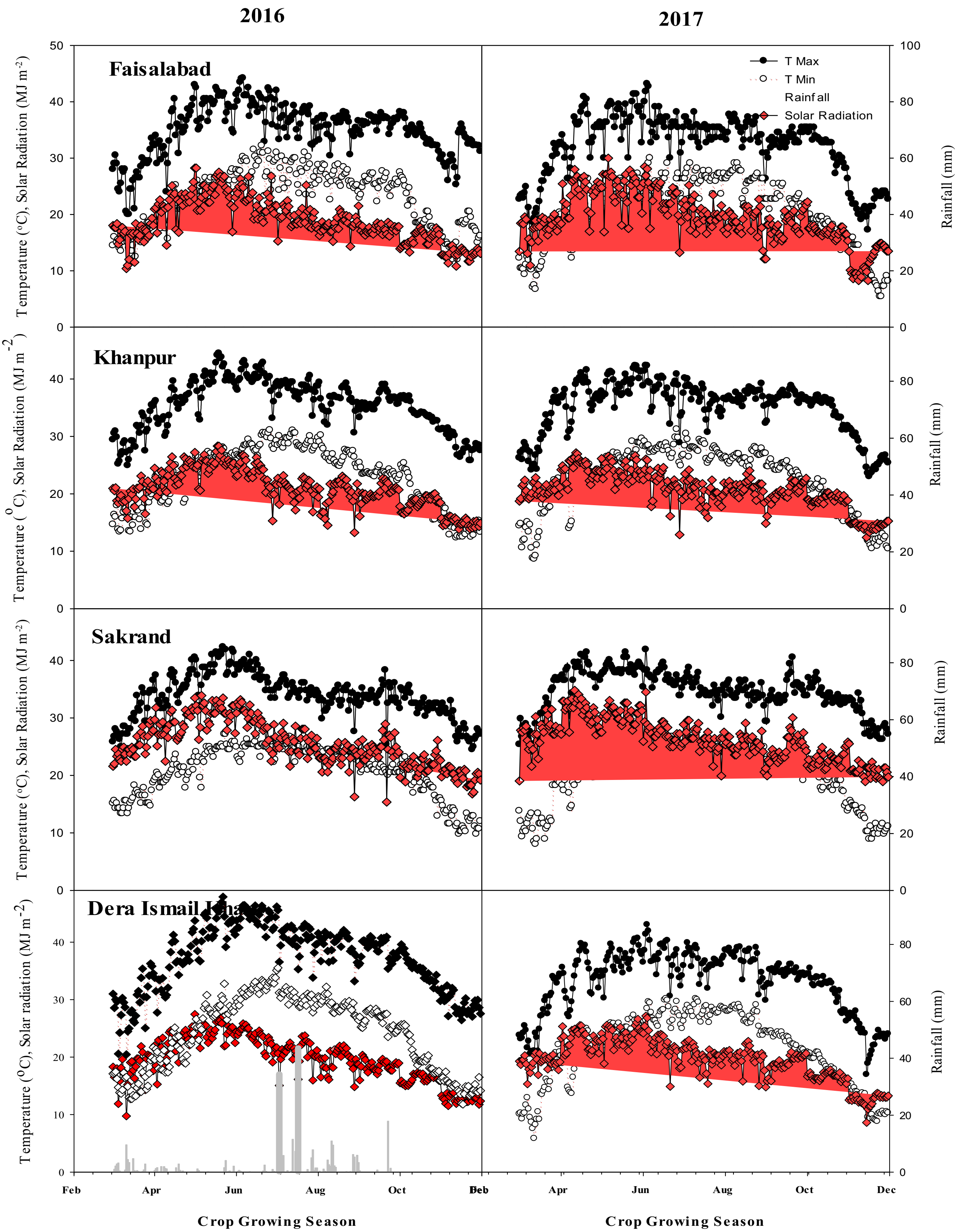

Fig. 1 Changes in weather parameters at all experimental sites during 2016 & 2017

emergence was quite different between the years and among the locations as well as sowing dates (Table 1). During the 1st year, the maximum time to emergence was noted in Faisalabad conditions while it was observed minimum in Khanpur location. During the 2nd year, the longest time for emergence was recorded at D I Khan which was also similar to Faisalabad whereas, the shortest time was noted in Khanpur and Sakrand experimental sites, respectively. The sowing dates also affected the mergence time and it was observed that the 1st sowing date, i.e. 1st March took maximum time to start emergence and the time was reduced as the sowing date was forwarded towards 15th May during both years of experimentation.

Time to first square (days) Squaring determines the crop potential to get higher seed cotton yield as it is the first fruiting body of cotton plant and it is mostly affected by crop nutrition and climatic conditions prevailing during this phase of the crop. It is evident from the data (Table 1) that time to start squaring was significantly affected by climatic variations during the years under study in all sowing dates at all the locations. The maximum days to initiate squaring were noted during the 1st year of study while these were lowered down during the 2nd year of experimentation. The data revealed that time to start squaring was in decreasing trend from Faisalabad to D I Khan to Sakrand up to Khanpur during both years of study. The sowing time also affected significantly this phenophase in terms that maximum time to initiate squaring was noted in 1st March sowing which was gradually decreased to minimum time in 15th May sowing (difference of 17–18 days from the 1st to the last sowing date during both years, respectively).

Time to first flower (days) Flowering is the prime physiological stage of cotton plant which determines the final productivity of the crop. Being the indicator of reproductive stage of the crop, very crucial with respect to prevailing resource availability and its utilization efficiency. Any pandemic situation (biotic or abiotic) may reduce the overall regional cotton productivity. The results showed the significant differences in time taken to start flowering by the crop among the years, sowing dates and varied locations (Table 1). The overall time to initiate flowering was more (>2 days, 4%) during 2016 than 2017 mainly due to higher temperature, more solar incidence and less rainfall during the 2nd season of crop experimentation. The time period between sowing to flowering was linearly affected by varying sowing dates and maximum time was noted in mid-March sowing which was reduced to minimum during mid-May sowing.

Time to first boll opening (days) Boll load in cotton tells the crop tendency to have better output of the available resources. It is mainly affected by its growth duration which in turns depends upon favorable climatic patterns along with

Table 1 Calendar days of crop phenology influenced by locations and sowing dates during both years of study (2016 & 2017)

Treatments	Days to Emergence		Days to Squarring		Days to Flowering		Days to Boll Opening		Days to Maturity	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
A. Locations										
Faisalabad	7.50 a	6.50 a	43 a	41 a	64 a	61 a	120 a	116 a	145 a	141 a
Khanpur	5.72 c	4.78 b	37 c	35 b	54 c	51 b	103 c	98 b	128 c	123 b
Sakrand	5.83 c	4.83 b	39 b	36 b	57 bc	54 b	108 bc	103 b	133 bc	128 b
D I Khan	6.50 b	7.17 a	40 b	40 a	60 b	59 a	114 ab	112 a	139 ab	137 a
HSD @ 0.05	0.527	0.733	1.661	2.464	3.612	3.090	6.106	5.699	6.106	5.699
B) Sowing Time										
1st March	8.66 a	8.08 a	48 a	47 a	71 a	68 a	128 a	124 a	153 a	149 a
15th March	7.83 ab	7.25 ab	45 b	43 b	66 b	63 b	121 b	117 b	146 b	142 b
1st April	6.92 bc	6.33 bc	41 c	40 c	61 c	58 c	114 c	110 c	139 c	135 c
15th April	5.83 cd	5.25 cd	38 d	36 d	56 d	54 d	108 d	104 d	133 d	129 d
1st May	4.92 de	4.33 de	34 e	33 e	52 e	49 e	101 e	97 e	126 e	122 e
15th May	4.17 e	3.67 e	31 f	29 f	47 f	45 f	95 f	90 f	120 f	116 f
HSD @ 0.05	1.085	1.373	2.780	3.024	3.318	3.244	3.716	3.943	3.716	3.943
Mean	6.39 A	5.82 B	39.64 A	37.90 B	58.81 A	56.32 B	111.31 A	107.24 B	136.31 A	132.24 B
HSD @ 0.05	0.333		0.805		1.369		1.518		1.518	
Interaction (Location × SD)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year × Location	**		NS		NS		NS		NS	

availability of water and nutrition. The present study indicated that time to 1st boll opening was significantly different among the years and sowing dates (Table 1). It is also noted that crop reproductive phase was significantly affected by locations during the 1st year while these locations behaved similar during the 2nd year of experimentation. Pronounced reduction in time taken to boll opening was experienced while changing sowing date from 15th March to 15th May during both years (19.19 & 19.87 %), respectively.

GDDs accretion during different crop growth stages and heat use efficiency

Thermal time for flower initiation

Thermal time accrual for flowering was varied among sowing dates during both years while similar GGDs were accumulated at all locations during only 1st year (Table 2). The overall mean data showed that maximum heat units were accumulated during 2016 which were 4.16 % higher than 2017 crop season due to less heat stress during 2016. Crop attained maximum thermal time for flowering initiation in Faisalabad conditions which was closely followed by Khanpur and Sakrand location while the minimum thermal time accrual was noted in D I Khan conditions during 2017. The data also revealed that thermal time accretion was showing quadratic trend as lower values at start of the season (15th March) reaching to maximum for 15th of April and then a decline was observed for 15th May sown crop during the course of study.

Thermal time to start boll opening and maturity (°C days)

Thermal time accretion for starting of boll opening and up to maturity were also variable among the years and sowing dates while thermal time to boll opening was not significantly different among the locations during the 1st year of the experiment (Table 2). During 2017, the higher heat units were accumulated at Khanpur and Sakrand which were closely followed by Faisalabad location while D I Khan gave lower light unit accrual during the study. Sowing dates also impacted heat unit accumulation showing maximum in early sown crop up to the 1st April sowing and further decline during late sown cotton crop (up to 15th May) during the study.

Thermal time to crop maturity was also significantly impacted by locations and sowing dates during both years of study (Table 2). The results revealed that thermal time accrual to maturity was higher but widely affected by the locations during 2016 than 2017 and Khanpur location harvested maximum light units during both years than all other locations under study. Among sowing dates, 1st April sowing accumulated the highest GDDs during both years while comparing with all other sowing dates and the last sowing date, i.e. 15th

Table 2 GDDs accrual for different phenological developments in various sowing dates at all four locations during 2016 and 2017

Treatments	GDDs to Flowering		GGDs to Boll Opening		GDDs to Maturity		Dry Matter Production (g m^{-2})	
	2016	2017	2016	2017	2016	2017	2016	2017
A) Locations								
Faisalabad	1162 ab	1160 a	2315	2346 a	2355 bc	2449 a	1512.6 b	1383.2 b
Khanpur	1147 ab	1150 a	2305	2251 ab	2497 a	2455 a	1274.0 c	1274.3 c
Sakrand	1210 a	1130 a	2395	2300 a	2450 ab	2372 a	1642.9 a	1474.6 a
D I Khan	1109 b	985.7 b	2247	2070 b	2303 c	2156 b	1236.5 c	1345.1 b
HSD @ 0.05	93.160	79.691	NS	186.04	110.02	103.30	60.91	68.19
B) Sowing Time								
1st March	1077 b	1043 c	2398 a	2292 a	2450 a	2395 b	1400.9 d	1500.3 a
15th March	1148 ab	1123 ab	2412 a	2345 a	2476 a	2455 ab	1456.2 c	1450.8 ab
1st April	1214 a	1186 a	2413 a	2359 a	2490 a	2470 a	1528.2 b	1405.4 bc
15th April	1212 a	1156 ab	2356 a	2274 a	2435 a	2394 b	1588.4 a	1361.1 cd
1st May	1190 a	1099 bc	2234 b	2159 b	2348 b	2281 c	1347.2 e	1301.6 d
15th May	1099 b	1036 c	2079 c	2021 c	2210 c	2152 d	1178.2 f	1196.7 e
HSD @ 0.05	85.524	77.171	91.687	94.503	64.162	68.87	37.92	64.77
Mean	1156.8 A	1107.3 B	2315.7 A	2241.7 B	2401 A	2358 B	1416.5	1369.3
HSD @ 0.05	26.932		34.05		25.98		NS	
Interaction (Location × SD)	NS	**	NS	NS	NS	**	**	*
Year × Location	NS		NS		NS		NS	
Year × Locations × SD	NS		NS		NS		NS	

may gave minimum light unit accrual for maturity. The interactive effect of location and sowing dates during 2017 (Fig. 2) showed that thermal time to crop maturity was sigmoid in nature and the maximum values were achieved at 1st April sowing at Faisalabad, Khanpur, and D I Khan location while 15th March accumulated maximum light units at Sakrand site. It was also noted that D I Khan location gave overall lower values for light unit accrual for crop maturity at all sowing dates in comparison to other locations and sowing dates, respectively.

Dry matter production

Dry matter accumulation is the prime parameter which is mostly affected by soil and weather attributes during whole plant life. Significant effect of sowing time was observed at all experimental sites on dry matter accumulation during both crop growing seasons (Table 2). There was higher dry matter accumulation (3.33 %) during 2016 than 2nd crop growing season. Mean of 2-year data suggested that final dry matter accumulation was maximum at Sakrand site which was 7.11, 17.19, and 18.26 % higher than Faisalabad, D I Khan, and Khanpur locations, respectively. It was shown that during 2016, dry matter production was geared up till 15th April sowing date whereafter, it declined to lowest dry matter production in late sown treatments. While during 2017, the maximum dry matter was produced in early sowing date (1st March) and it was lowered down to minimum during last sowing date (15th May) at all locations (Fig. 3).

Heat use efficiency (kg °C days^{-1})

Heat use efficiency (HUE) determines the potential of the crop to enhance crop biomass in changing climatic conditions which in turns produce higher seed cotton yield. The data (Table 3) showed that HUE was differed among the years, locations, and sowing dates, respectively. The mean data indicated that HUE was found higher during the 1st year in comparison to its values during the 2nd year of experimentation. It was also noted that the maximum HUE was observed at Sakrand while it was lowered to minimum in D I Khan conditions. However, sowing time showed quadratic behavior with respect to HUE during both years, being lower during earlier sowing dates, reaching to maximum during 15th April sowing date and once again lowered down in last sowing date (15th May).

Yield-related parameters

The significant differences were noted in opened number of bolls per plant with respect to sowing dates at all the locations under study, however, two seasons were similar in this regard (Table 3). The overall trend of boll opening at all experimental sites was different and at Khanpur and D I Khan locations, early sown crop (1st March) gave higher mature bolls, which were gradually decreased towards end of the season (15th May) but a sharp decline was noted in D I Khan conditions. While at Faisalabad, 15th March sowing gave higher number of opened bolls which were also gradually decreased towards end of the sowing season. Very unique trend was noted at Sakrand where, comparatively higher number of bolls were shown in 15th March to 15th May sowing dates with maximum opened bolls in 15th April sowing and the lowest in 1st March sowing.

Average boll weight (ABW) was significantly affected by the locations and sowing dates during both years of study but there was no significant difference between the seasons (Table 3). The two year mean data fairly described that the ABW was different among the sowing dates at all four locations under study and the overall higher boll weights were produced at Sakrand location in all sowing dates reaching to maximum in May sowings (1st and 15th). In Faisalabad, early sown crop (1st & 15th March) produced heavier mature bolls than subsequent sowing dates towards 15th May. While in

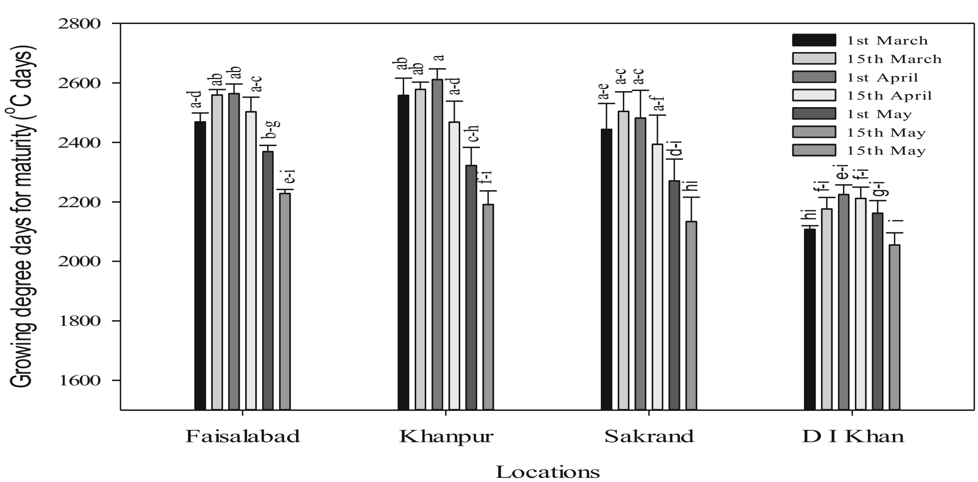

Fig. 2 Growing degree days for sowing to maturity of cotton crop during 2017

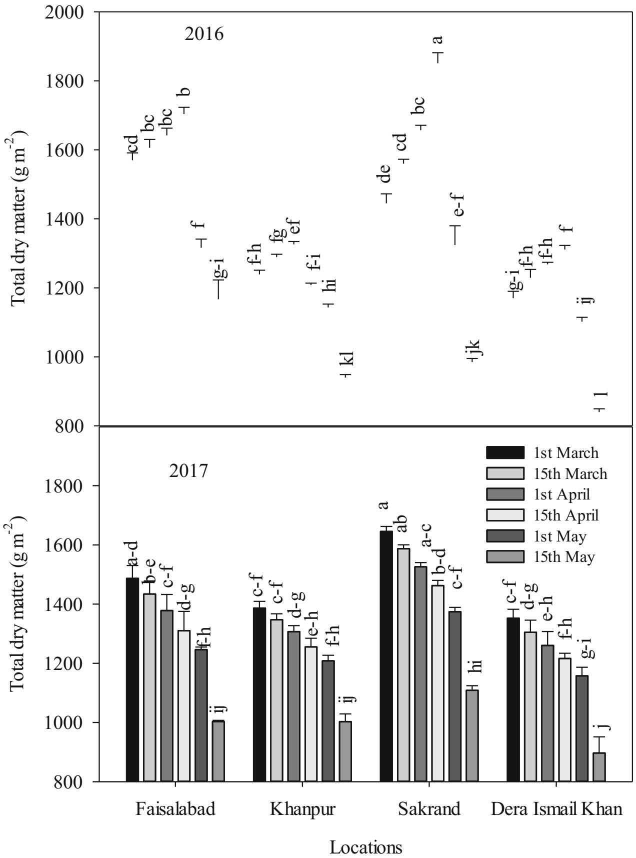

Fig. 3 Total dry matter (g m^{-2}) produced in different sowing dates at all locations during both years (2016 & 2017)

Khanpur, higher weights of mature bolls were recorded in 1st April sowing and much lighter bolls were given in late sown crop. The test variety, FH 142 behaved differently in D I Khan conditions where it gave lighter bolls in early sowing reached to maximum boll weight in 15th April sowing and lower boll weights were once again noted in late sowings (1st & 15th May).

The final seed cotton yield was also significantly different among the locations, sowing dates and between the two comparative seasons and more seed cotton yield (13.08%) was noted in the 1st year than the 2nd year (Table 3). The seed cotton yield was maximum in 15th April sowing in Sakrand conditions which was closely followed by 15 days earlier (1st April) and 15 days later sowing date during the 1st year while only 1st April sowing during the 2nd year at the same location. 1st April sowing at Faisalabad and 1st April to 1st May sown crop in Khanpur also gave similar cotton yield during 2017. It was also noted that the cotton yield was increased till 15th April in Faisalabad, Sakrand, and D I Khan conditions but it attained its peak in 1st April sowing at Khanpur location during 2016 crop season while 1st April gave higher yields in Faisalabad and D I Khan conditions during 2nd year (2017). The overall minimum seed cotton yield was given by 15th May sowing irrespective of location differences during both crop seasons (Fig. 7).

The higher GOT values were observed during 2016 than 2017 crop season. The GOT was differed among the locations and sowing dates during both years and the maximum turn-

Table 3 Changes in yield-related parameters in different sowing dates at all four locations during the course of study

Treatments	Average Boll Wt. (g)		Opened Bolls per plant		Seed Cotton Yield (kg ha^{-1})		Heat Use Efficiency		GOT (%)	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
A) Locations										
Faisalabad	3.31 a	2.93 b	44.83 b	50.67 b	2468.07 c	2357.59 c	1.06 c	1.00 b	37.90 b	37.01 b
Khanpur	2.77 b	2.61 b	54.67 a	55.83 ab	2712.37 b	2601.00 b	1.17 b	1.16 a	38.73 b	37.14 b
Sakrand	3.46 a	3.49 a	64.00 a	59.67 a	3168.09 a	2748.22 a	1.33 a	1.20 a	40.59 a	38.15 a
D I Khan	2.47 b	2.85 b	40.83 b	36.00 c	2267.23 d	1519.49 d	1.00 c	0.73 c	36.36 c	35.31 c
HSD @ 0.05	0.315	0.399	9.616	6.219	97.94	133.40	0.072	0.131	0.770	0.41
B) Sowing Time										
1st March	2.98 ab	3.14 a	51.75 a	56.00 a	2452.02 d	1923.47 d	1.02 d	0.83 d	36.15 d	35.37 d
15th March	3.03 ab	3.14 a	55.00 a	58.25 a	2679.39 c	2458.24 b	1.11 cd	1.04 b	37.42 c	36.18 c
1st April	3.10 a	3.02 ab	53.00 a	51.75 ab	2964.33 b	2699.18 a	1.23 b	1.14 a	39.39 b	37.23 b
15th April	3.15 a	3.05 ab	56.50 a	53.25 ab	3193.17 a	2641.89 a	1.36 a	1.16 a	40.36 a	38.62 a
1st May	2.95 ab	2.90 b	48.75 ab	45.75 bc	2554.05 cd	2223.76 c	1.14 bc	1.03 b	39.29 b	37.55 b
15th May	2.81 b	2.57 c	41.50 b	38.25 c	2080.68 e	1892.91 d	1.00 d	0.94 c	37.88 c	36.45 c
HSD @ 0.05	0.236	0.223	8.529	9.771	198.36	158.21	0.111	0.073	0.647	0.411
Mean	3.00	2.97	51.08	50.54	2653.94 A	2306.58 B	1.09 A	0.99 B	38.41 A	36.90 B
HSD @ 0.05	NS		NS		19.088		0.08		0.577	
Interaction (Location × SD)	NS	NS	**	**	**	**	NS	NS	NS	**
Year × Location	NS		NS		**		NS		NS	
Year × Locations × SD	NS		NS		NS		NS		NS	

out was observed in Sakrand site and 15th April sowing date during both years in comparison to other sites and sowing dates, respectively (Table 3), while the lowest GOT was estimated at D I Khan location during both years. It was also noted that sowing of crop early in season showed minimum response towards lint production.

Discussion

Cotton grows well in dry and hot climate and its growth period is likely to be affected mainly by soil and environment of the particular site. Its growth and development is mostly impacted by climate change attributes like photothermal fluctuations, amount and intensity of rainfall, relative humidity and wind (Ullah et al. 2017). These fluctuations have played vital role in the reduction of reproductive growth stage and escalating transpiration rate resulting in reduced cotton yield (Rahman et al. 2017). As the climatic conditions differ, the whole water cycle is changed by variation in rainfall, its intensity and timing, resulted effects like runoff, ET and the frequency and intensity of either floods or droughts (Mubeen et al. 2019). Present study indicated that cotton variety FH 142 showed vibrant performance regarding phenological advancement at varied locations and sowing dates resulting in quite dynamic yield production (Arshad 2017; Shah et al. 2017; Bilal et al. 2019). Among environmental attributes affecting the crop phenology, temperature is the main factor, distressing plant processes resulting in differential timing of squaring, flowering, boll formation and maturity (Mauney 1986). Shah et al. (2017) also reported less time to accomplish crop growth phases with delay in sowing time from February to May sowing in dry conditions of Southern Punjab, Pakistan. Rahman et al. (2017) also found that phenological advancement in

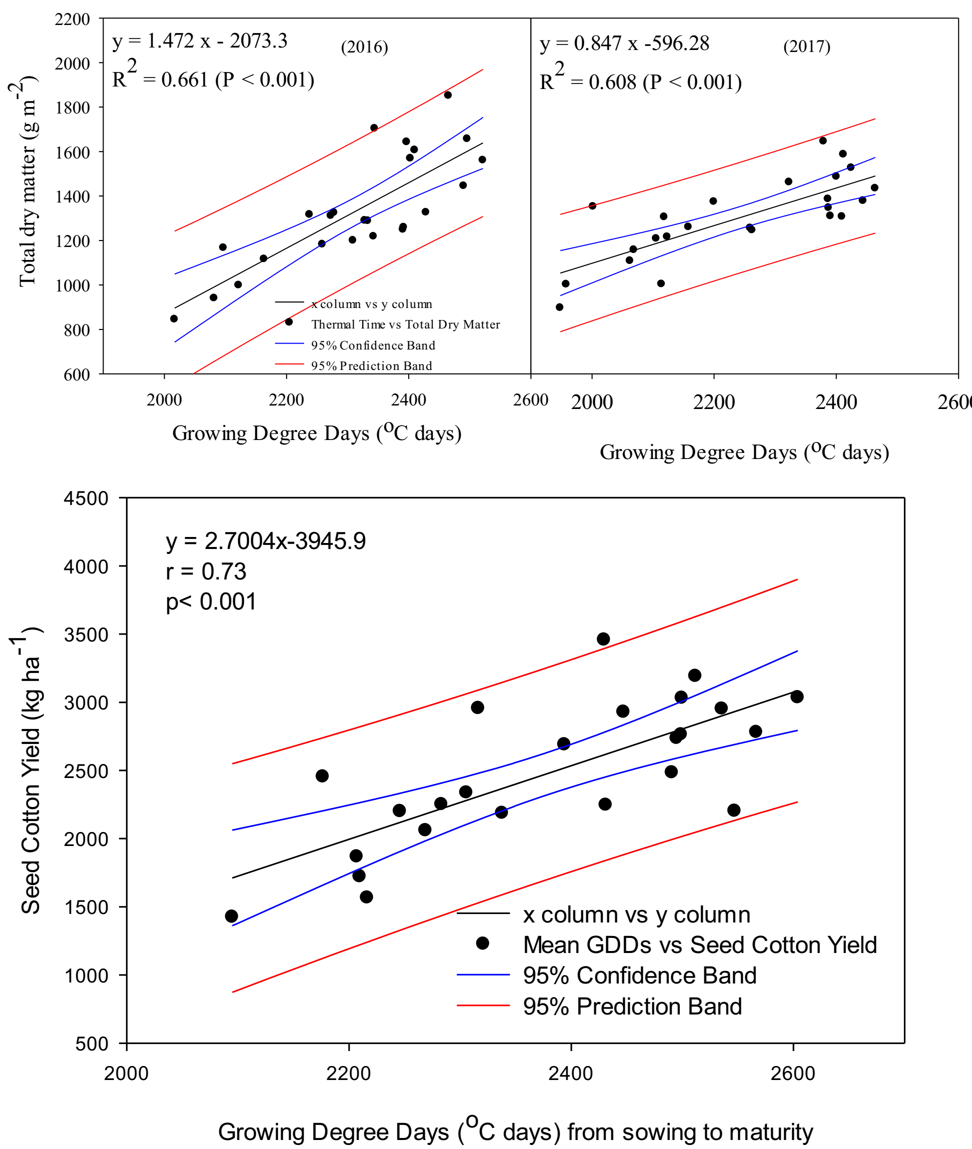

Fig. 4 Relationship between the thermal time (°C days) and respective dry matter accumulation along with seed cotton yield during the course of study

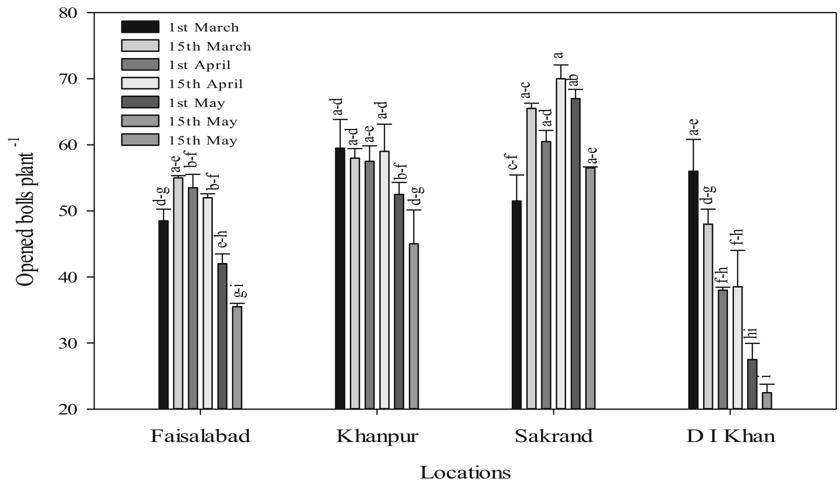

Fig. 5 Number of opened bolls plant^{-1} in different sowing dates at all locations (2-year mean data)

cotton was significantly affected by sowing time and there was gradual decrease in time to start squaring with each 20 days delay in sowing time between 10th March to 21st June. It may also be due to least incidence of low temperature (<12 °C) stress during crop establishment stage favoring completion of crop phenological phases at higher pace (Rahman et al. 2016; Shah et al. 2017; Bilal et al. 2019).

Cotton is considered as heat loving crop which requires varied level of temperatures during germination (32–34 °C), vegetative phase (25–27 °C), and for whole crop growing season (21–22 °C). Growing Degree Days are considered as pragmatic tool in phenological studies as it narrates the dependence of plant growth, development and maturity to air temperature. Plant growth is totally dependent on the amount of heat units it consumed during its life cycle (Sangameshwari et al. 2019). Degree days accrual was also differed among sowing dates at distinct locations confirming the results reported by Rahman (2017), Arshad (2018) and Shah et al. (2017). The least GDDs accumulated in last sowing date may be attributed to short vegetative growth period and more heat occurrence during reproductive phase resulting in exaggerated crop movement towards boll opening (Bilal et al. 2019) as it takes 12–15 days to sprout if its temperature is 15°C and its time is squeezed to only 6 days when it is grown at about 20 °C (Sangameshwari et al. 2019). There was strong positive correlation among the seasonal thermal time and resultant dry matter accumulation during both years (Fig. 4.16) clearly indicating that higher thermal time may give rise to higher dry matter production during the crop growth season. Rahman et al. (2016) also proved the similar behavior of the cotton crop while studying the implications related to varied sowing dates and their impact on crop phenology. Rahman et al. (2017) and Kumar et al. (2012) reported that 15 April sown cotton crop required more days to reach particular phenological stage, whereas lesser days were recorded under 15 May sowing. The heat units needed to produce open bolls from flowering stage were significantly reduced in late sown crop under rainfed condition (Hebbar et al. 2002). Prakash

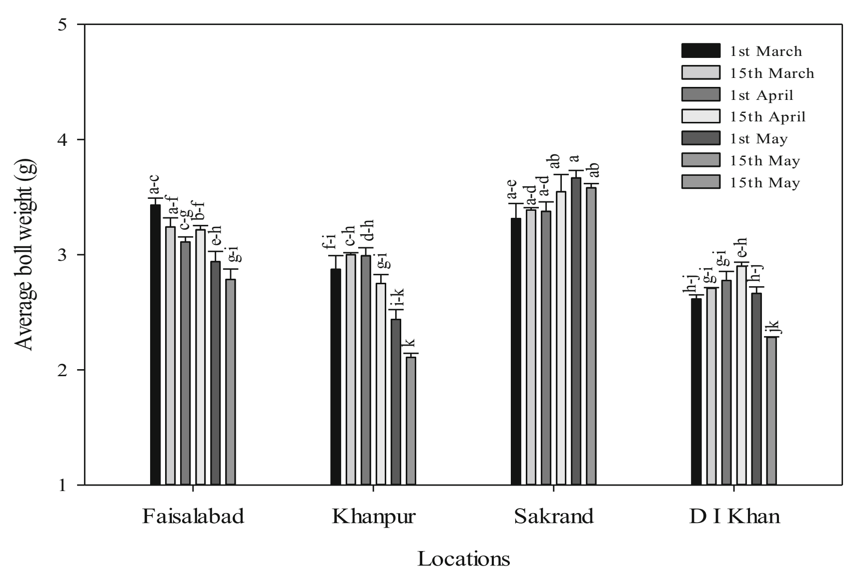

Fig. 6 Average boll weight (g) in different sowing dates at all locations (two year mean data)

et al. (2010) reported that earlier sown cotton experienced the greater cumulative GDDs in comparison with late sown crop showing the lowest GDDs accumulation. The final seed cotton yield and its parameters were varied among locations as well as sowing dates. The main attributes like LAI, TDM, GDDs, and HUE were significantly affected by the treatments resulting in less number of opened bolls, ABW and SCY during late sowings (Ullah et al. 2017; Arshad et al. 2017; Bilal et al. 2019) while the non-significant differences in ABW were also reported at varied sowing dates (Salih, 2019) (Figs. 5, 6).

The variation in final cotton yield at different locations has been considered by other scientists working on cotton crop due to variation in soil, cultivar, climatic conditions and crop management practices like sowing dates, irrigation and fertilizer application. As the water is considered as the most limiting factor for cotton based cropping system in arid to semi-arid condition of cotton growing zone of Pakistan (Mubeen et al. 2019). Bilal et al. (2019) reported that cotton yield was different at varied locations (Faisalabad, Multan and Bahawalpur) and the maximum cotton yield was observed in Multan conditions which was followed by Bahawalpur and Faisalabad, respectively. While the normal sowing date (15th April) produced highest cotton yield (2910 & 3044 kg ha^{-1}) during 2013 & 2014, respectively surpassing all earlier and later sowing dates at distant locations in Punjab-Pakistan. Arshad (2017) also reported similar findings while working at Faisalabad, Sahiwal and Multan locations. Rahman et al, (2016) also showed similar trend of seed cotton yield at varied sowing dates under Faisalabad conditions. These variations are the result of change in environmental factors (especially temperature) and soil attributes affecting

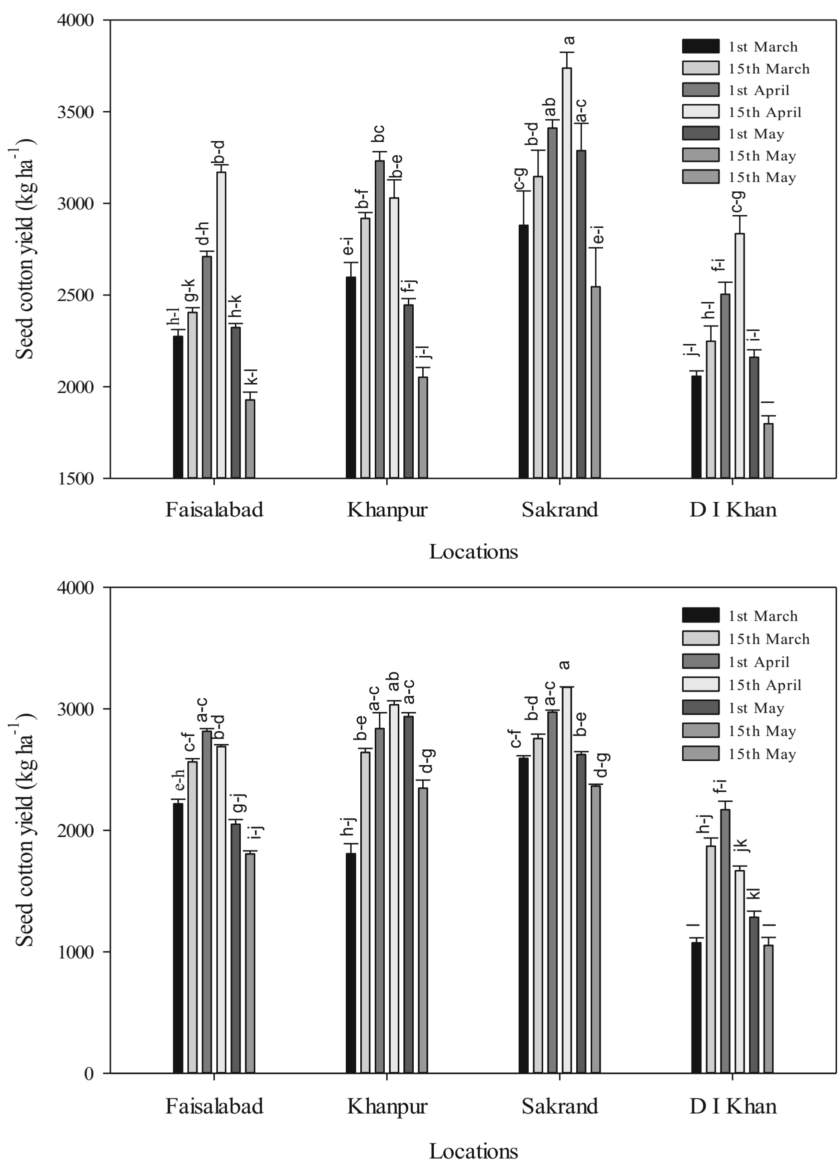

Fig. 7 Seed cotton yield (kg ha^{-1}) as influenced by different sowing dates at different locations during 2016 and 2017

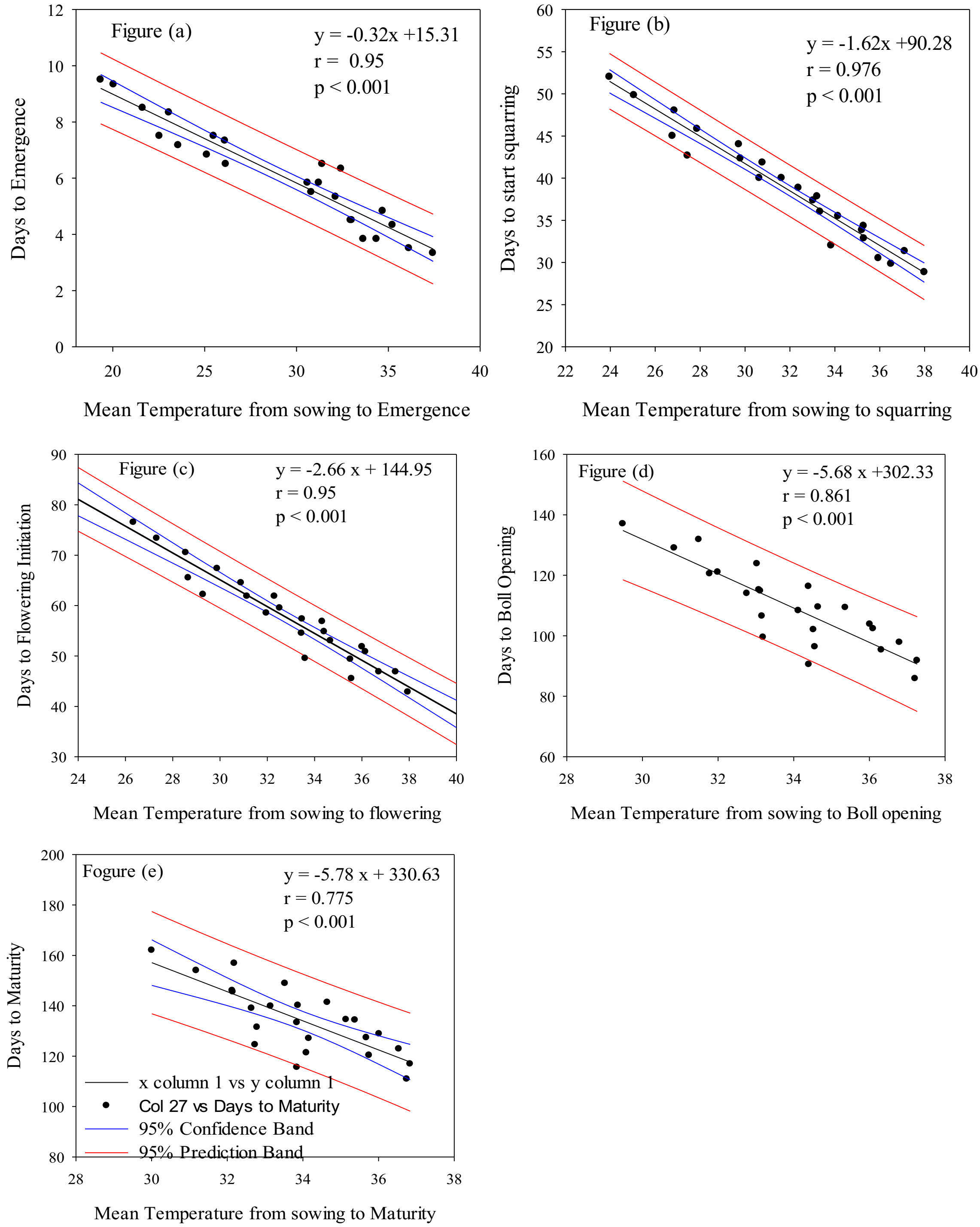

Fig. 8 Effect of mean temperature on time form sowing to emergence (a), squaring (b), flowering (c), boll opening (d) and crop maturity (e) during the study period

crop sustaining processes like photosynthesis and transpiration which ultimately affect crop yields (Bilal et al. 2019) (Figs. 7, 8).

The seed cotton yield trend was more homogenous among the locations during 2017 than 1st year of experimentation due to varying rainfall intensity during 2016 and drier conditions during 2017 at all locations, respectively. This resulted in good growth and development of the crop and less pest pressure and hence, higher seed cotton yield during 2017 crop season. As the changes in climatic attributes at varied locations affect the crop photo-assimilation and resulting in variation of economical yields at different locations. Furthermore, it also pertinent to report that climatic warming may harm the net crop returns due to increased water requirements and reduced crop photosynthesis rate (Ullah et al. 2018). The higher crop yield at Sakrand may be attributed to better soil conditions, favorable environment with least rainfall without hitting the crop by higher intensity of heat stress resulting in better yield contributing factors like higher bolls per unit area with higher mass, more sympodial branches per plant, fairly higher crop growth parameters like LAI, TDM, and crop growth rate (data not shown here). This also proved that seed cotton yield is the combined effect of individual yield contributing factors and its particular environmental conditions (Wajid et al. 2010). There were also more sunshine hours available to crop at Sakrand site which were more efficiently harvested by the crop producing more photo assimilates per unit of light absorbed by the crop canopy during the crop growing season. The favorable environmental conditions resulted in better resource use efficiency in terms of solar radiation, soil fertility and available water to the crop in that particular location as plant canopy temperature, ambient air temperature along with atmospheric vapor pressure deficit have proved their influence on crop water use and overall its irrigation requirements during its growth period (Usman et al. 2009).

Conclusion

It may be concluded from the present investigation that temperature is the key environmental indicator for cotton crop phenological advancement from emergence to boll opening irrespective of the variation in locations under arid to semi-arid climates of the cotton growing zone of Pakistan. Phenological traits along with seed cotton yield were found significantly affected by the locations and sowing time, respectively. The higher temperatures during vegetative/ reproductive stages harm the overall progress of the crop resulted in loss in final seed cotton yield over the locations. Meanwhile, varying sowing dates may be utilized to mitigate the problem intensity and can give higher lint returns at any location. In this way, crop can get better heat units to reach the crop maturity well in time and good light harvesting is possible in the current changing climatic scenarios.

Novelty of the study This study covers whole cotton growing area of the country irrespective of provincial boundaries and it is tried to get insight of the concept of environmental attributes like temperature, light units and their utilization for estimating cotton growth, development and yield attributes under diverse environments from semi-arid in Central, Southern Punjab and KPK to Arid in Sindh. The other studies are mostly limited either to one location or one growing area in cotton growing zone of Punjab/ KPK or Sindh (Arshad et al. 2017; Bilal et al. 2019; Rahman et al. 2017; Ullah et al. 2017; Deho et al. 2012 etc.).

Potential areas for future studies The present study elaborated the potential impacts of environmental attributes on cotton crop phenology, growth, development, and yield contributing parameters under cotton growing zone of Pakistan. In future, these studies should be extensive in nature covering more locations and cotton cultivars and employing more advance techniques like multi-model future projections, remote sensing tools for getting more precision in results and their analysis on modern ways to understand the system vigorously.

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Author information The authors belong to University of Agriculture Faisalabad, their professional profiles are also available on university website and can be searched at www.uaf.edu.pk.

Author contribution MAM—is the main executer of this research, who sampled, analyzed, and travelled to different areas in different seasons for the collection of plant dat from sowing to harvesting.

FR—acted as supervisor of study, he planned the thematic layout, assessment of seasonal variation as well as spatio-temporal assessments, provided lab facilities and helped with field studies as well.

TK—played important role in funding provision for travelling, sampling, laboratory chemical analysis, statistical analysis and eco-physiological aspect studies along with guidelines to synchronize the project and this study objectives achievements.

MY—acted as co supervisor of the study, helped with data analysis in his lab, data interpretation and analytical work guidance for assessment.

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Data availability Will be available.

Declarations

Ethics approval and consent to participate All co-authors have given consent to corresponding author to submit on behalf of them. No ethical studies are required in this plant study.

Consent for publication All co-authors have given consent to the corresponding author.

Competing interests The authors declare no competing interests.

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