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Full Length Article

Relay Intercropping Improves Growth and Fiber Quality of *Bt* Cotton

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Abstract

The optimal time of wheat harvest is the second fortnight of April, while *Bt* cotton is sown in March in cotton-based cropping systems of Pakistan. There is a time conflict of four to six weeks between harvesting of wheat and sowing of *Bt* cotton. Relay-intercropping of cotton in wheat crop near to maturity could help to resolve the conflict. The information regarding the effect of relay-intercropping on growth and quality of cotton is scanty. This two-year study compared the growth and fiber quality of relay-intercropped *Bt* cotton (sown in early/late March) in standing wheat crop with conventionally-tilled (CT) cotton planted after wheat harvest in late April. The relay-intercropped cotton was sown on ridges/beds in wheat, whereas CT cotton was sown after wheat harvest in late April or sown on fallow land in early or late March at Multan and Vehari sites. The CT *Bt* cotton grown on fallow land in early March had the best performance as indicated by plant growth and fiber quality. However, the relay-intercropped *Bt* cotton in bed-sown wheat had better growth and fiber quality than the CT cotton planted after wheat harvest in late April. At both sites, the taller plants and higher biomass production were recorded in relay-intercropped Bt cotton in bed-sown wheat in early March as compared with the CT cotton sown after harvest of flat-sown wheat in late April. Fiber firmness, its uniformity, length and strength were also improved in the relay-intercropped *Bt* cotton in bed-sown wheat in early March as compared to CT cotton sown after wheat harvest in late April. In conclusion, relay intercropping of *Bt* cotton in the standing wheat during early March improved plant growth and fiber quality in cotton-wheat cropping system.

Keywords: B*t* cotton-wheat cropping system; Conventionally-tilled cotton; Relay intercropping; Allometry; Fiber quality

Introduction

Cotton-wheat cropping system is extensively practiced in South Asia, including Pakistan as well as many other parts of the world. Cotton has higher economic benefits than wheat because of its high yield potential and longer crop duration. Conventional and transgenic cotton (so-called "*Bt* cotton") are sown in these cropping systems. The *Bt* cotton has been rapidly adopted in cotton-wheat cropping system due to its several benefits (Malik *et al.*, 2018). The resistance of *Bt* cotton against chewing insects and high yield potential than conventional cotton led to the acceptance/adoption of *Bt* cotton in cotton-based cropping systems and strategies, particularly cotton-wheat cropping system (Ali and Abdulai, 2010; Yasmeen *et al.*, 2018). However, the adoption of *Bt* cotton has rendered severe challenges, including high demands of irrigation water, fertilizers, labor and other inputs. The high yield potential of *Bt* cotton is directly related with its extended growth period (Dong *et al.,* 2005), which has created a serious time conflict of 4–6 weeks between the *Bt* cotton sowing and wheat harvest. In cotton-wheat cropping system (CWCS) in Pakistan, wheat is harvested in late April/early May, while the optimum sowing time for Bt cotton is mid-March (Shah *et al.,* 2017). As consequence, ~70% of wheat growers in CWCS zone showed interest to divert some areas to *Bt* cotton instead of wheat and a decrease of 8.2% in wheat area was noted between 2008 and 2010 (Sabir *et al.,* 2011).

This situation may impact the future food security in Pakistan, as most of wheat production comes from cotton-wheat and rice-wheat cropping systems (Shiferaw *et al.,* 2013). Therefore, finding appropriate agronomic practices to ensure the sowing of both crops without compromising yields is the dire need of the time.

Optimum planting time is most important for attaining the highest yields of field crops. Planting at optimum time ensures high crop productivity and such timing varies among agro-climatic zones (Ali *et al.,* 2004; Hussain *et al.,* 2012a). Early planting of cotton ensures better utilization of rainfall and sunlight and plants produce more bolls than late-planted cotton crop (Pettigrew, 2002). On the other hand, late sowing increases the time period between seed sowing and seedling emergence, delays the emergence of first square and first flower, and decreases plant survival and seed cotton yield (Ali *et al.,* 2004).

In this scenario, relay intercropping of *Bt* cotton in standing wheat during March is a viable option to grow Bt cotton in furrows of ridge-sown wheat and on both sides of beds in bed-sown wheat. Relay intercropping is referred to sowing of second crop in standing first crop near to its harvest. The relay-intercropping of cotton in wheat will lead to overlapping of reproductive phase of wheat and seedling phase of cotton, and the next wheat crop will be sown after the final picking of the cotton crop in late October (Zhang *et al.,* 2007). In an earlier study, the total system productivity and per unit area net returns were highest in relay-intercropped *Bt* cotton in wheat than the sole cotton cropping on fallow land during early March (Shah *et al.,* 2016). Saeed *et al.* (1999) also unveiled more income in different relay cotton-based intercropping systems.

The relay-intercropping of cotton in wheat is not a common practice; however, we hypothesize that this may be an alternative to avoid the overlapping of wheat harvesting and cotton sowing. The adoption of any novel agronomic technique must ensure both quantity and quality of the crop. Recently, relay intercropping of *Bt* cotton in bed-sown wheat increased not only cotton production but also overall yield in CWCS (Shah *et al.,* 2016). Thus, the time conflict of 4–6 weeks can be resolved by relay-intercropping of *Bt* cotton in standing wheat crop (Shah *et al.,* 2016). As cotton is the most important fiber crop, fiber quality is also an important output and information about how relay *Bt* cotton intercropping affects fiber quality in CWCS is still lacking. Thus, this study compared the growth and fiber quality of relay-intercropping *Bt* cotton (sown in early/late March) in wheat against CT cotton sown after wheat harvest in late April or CT cotton sown on fallow land in early or late March at two different sites, *i.e*., Multan and Vehari. It was hypothesized that relay-intercropping of cotton in wheat crop will improve the growth and fiber quality of *Bt* cotton in the prevailing cotton-wheat cropping systems of Pakistan. The results of the study will help to improve the growth and fiber quality of *Bt* types in cotton-based cropping systems of the country.

Materials and Methods

Experimental Sites, Plant Material and Cropping Systems

This field study was conducted in Vehari (71.44°E, 29.36°N, 135 m a.s.l.) and Multan (71.50°E, 30.26°N, 123 m a.s.l.), Pakistan during two crop seasons, i.e., 2011/12 and 2012/13. Climate at both locations is semi-arid and soil was clay-loam in Vehari, while it was silty-clay-loam in Multan. Soil was analyzed for physical and chemical properties to evaluate soil fertility prior to sowing (Table 1). Weather data were recorded during whole experiment period and are summarized in Table 2.

Seeds of wheat (*Triticum aestivum* L.) cultivar Punjab-2011 and Bt cotton (*Gossypium hirsutum* L.) cultivar MNH-886 were obtained from Ayub Agricultural Research Institute (AARI), Faisalabad and Punjab Seed Corporation, Khanewal, Pakistan, respectively. Different treatments included in the study were; cotton sowing on CT field in early (S1) and late (S2) March on fallow land, cotton sowing on CT field during late April after harvesting of wheat (sown on flat surface) (S3), relay-intercropping of cotton on both sides of beds in bed-sown wheat (BSW) in early (S4) and late (S5) March, and relay-intercropping of cotton in furrows of ridge-sown wheat (RSW) in early (S6) and late (S7) March.

Experiments were laid out according to randomized complete block design with factorial arrangement. The locations were regarded as the main factor, whereas cropping system treatments were treated as sub-factor. The net plot size was 3 × 5 m.

Wheat Crop Husbandry

A presoaking irrigation of 100 mm was given as surface flooding through cutthroat flumes before tillage practices and crafting fine seedbed. Seedbed was prepared by ploughing with cultivator (2 times) and then planking. Manual sowing of wheat was done with single row drill in 0.25 m spaced rows keeping seed rate of 125 kg ha^{-1} on flat seedbed, ridges or beds according to the cropping system treatments. In both years, sowing was done on Nov. 15 and 17 in Multan and Vehari, respectively. Wheat fertilization was done with 150 and 100 kg N and P ha^{-1}, respectively using urea (46% N) and triple super phosphate (46% P_2O_5) as sources. The N was applied in two equal splits where 1st split was given before sowing, whereas 2nd split was provided with first irrigation. However, whole amount of P was applied at sowing due to less mobile nature of P in soil. The first irrigation to wheat crop was done at tillering stage. The succeeding irrigations were done at jointing, booting and grain-filling stages. Crop was irrigated at each growth stage at both sites to avoid moisture stress. Mature wheat crop was harvested on Apr. 18 and 20 in Multan and Vehari, respectively.

Table 1: Soil physical and chemical characteristics at both sites before cotton sowing (2011) and at cotton harvest (2012 and 2013)

Characteristics	Unit	Multan			Vehari		
		2011	2012	2013	2011	2012	2013
		Physical Analysis					
Sand	%	28.40	24.40	27.85	28.50	28.70	28.90
Silt	%	51.70	51.65	52.40	50.60	50.50	50.55
Clay	%	19.90	19.95	17.75	20.90	20.80	21.65
Textural class		Silty clay loam			Clay loam		
		Chemical Analysis					
pH		8.60	8.80	8.55	8.40	8.20	8.35
EC	dS m^{-1}	3.23	3.24	3.20	2.85	3.06	2.97
Organic matter	%	0.68	0.79	0.75	0.69	0.73	0.76
Total nitrogen	%	0.04	0.07	0.07	0.06	0.07	0.08
Available phosphorus	mg kg^{-1}	4.85	5.97	7.27	4.98	6.12	7.20
Available potassium	mg kg^{-1}	332	310	333	300	325	333

Table 2: Weather data at both experimental sites during the course of study

Months	Multan					Vehari				
	Temperature (°C)		Mean monthly relative humidity (%)	Total monthly rainfall (mm)	Mean sunshine (h per day)	Temperature (°C)		Mean monthly relative humidity (%)	Total monthly rainfall (mm)	Mean sunshine (h per day)
	Max.	Min.				Max.	Min.			
November 2011	28.33	14.62	75.84	0.00	6.91	27.86	14.33	76.32	0.00	7.01
December 2011	22.19	7.03	71.53	0.00	6.75	22.03	6.86	72.17	1.24	6.67
January 2012	19.10	5.34	77.79	15.00	6.43	18.89	5.11	80.16	19.57	6.32
February 2012	20.51	6.95	63.85	0.00	7.19	20.51	6.75	67.73	0.00	7.28
March 2012	27.40	13.85	55.13	0.00	6.72	27.22	13.48	56.17	0.87	6.88
April 2012	32.83	20.61	63.92	24.72	8.23	31.18	19.88	64.67	32.17	8.19
May 2012	39.40	25.68	55.85	1.0	8.54	39.94	25.34	57.47	2.22	8.36
June 2012	39.40	28.63	61.15	0.00	8.19	38.02	28.55	60.12	0.00	7.73
July 2012	38.13	28.82	66.64	16.92	7.81	37.86	28.53	67.27	17.75	7.67
August 2012	35.61	27.97	74.16	10.94	7.09	35.42	28.08	73.79	19.92	7.01
September 2012	33.10	25.67	85.55	167.17	7.03	32.89	25.57	85.05	193.65	6.97
October 2012	31.71	18.90	72.59	3.22	8.33	31.27	18.61	74.14	0.00	8.54
November 2012	26.77	13.11	84.17	0.00	6.11	26.49	13.05	83.76	0.00	7.49
December 2012	21.88	7.81	83.52	4.00	6.12	21.58	7.97	82.19	5.19	6.68
January 2013	18.8	5.90	80.45	0.00	5.62	18.25	5.91	79.91	0.00	5.74
February 2013	20.63	11.49	87.37	72.93	5.74	20.05	12.05	87.12	89.32	5.91
March 2013	28.15	15.93	75.65	16.73	8.43	27.85	15.68	74.64	12.98	7.96
April 2013	33.42	20.57	60.95	1.33	7.78	33.26	20.27	62.12	0.00	8.11
May 2013	40.37	25.51	54.92	0.00	9.86	41.07	25.43	55.47	0.00	7.92
June 2013	38.87	29.23	67.85	50.70	8.19	39.02	29.11	64.53	63.11	8.28
July 2013	38.19	29.85	64.51	16.91	7.92	38.11	29.59	65.44	0.00	8.18
August 2013	35.22	27.98	72.22	74.23	7.17	35.05	27.87	73.32	3.21	7.27
September 2013	33.90	24.95	61.87	3.22	7.87	33.95	24.72	63.33	7.54	7.86
October 2013	21.75	18.67	71.82	2.19	8.11	21.63	19.02	72.65	0.00	8.19

Source: Meteorological Section of Central Cotton Research Institute Multan, Pakistan and Meteorological Section of Cotton Research Station, Vehari, Pakistan

Relay Intercropped *Bt* Cotton

The land was prepared as described for wheat when considering treatments S1 and S2, *i.e*., CT cotton on fallow land in early and late March. *Bt* cotton was manually dibbled with plant-to-plant distance of 0.2 m and row-to-row distance of 0.75 m. After the harvest of flat-sown wheat in late April (S3), CT cotton was manually dibbled as described above. In BSW, cotton was relay intercropped on both sides of beds (0.75 m wider) in early (S4) and late (S5) March. In RSW, cotton was relay-intercropped in furrows of 0.75 m spaced ridges in early (S6) and late (S7) March using seed rate of 15 kg ha^{-1}. The moisture from third irrigation *i.e*., at booting stage and fourth irrigation *i.e*., at grain filling stage applied to wheat crop were used to plant relay-cotton in different wheat systems. Cotton fertilization was done with 250 and 200 kg ha^{-1} N and P, respectively using the same sources as described in wheat crop. Unlike wheat, N was applied in three equal splits where first split was applied at sowing, whereas remaining splits were applied at 1st and 2nd irrigation. Whole P, like wheat, was applied at the time of sowing. Hoeing was done twice to control weeds. The first irrigation crop was done at 35 days after sowing of cotton. The subsequent irrigations were done at 15 days interval until the final crop harvest. After wheat harvest on Apr. 18 and 20 in Multan and Vehari, stubbles were incorporated into the soil. Final picking was taken during the last week of October in both years and locations.

Allometry

Ten randomly selected and tagged plants were used to monitor the crop allometry from each treatment unit. Plant allometry was evaluated at fortnightly intervals, between 60 days after sowing (DAS) and crop maturity. Plant height was measured with the help of measuring tape from the plant base (point where the stem comes out of the soil) to the tip of main stem. Leaf area index (LAI) was estimated by dividing leaf area to ground area. Leaf area meter (MK2, DT, Delta T Devices, Cambridge, U.K.) was used to measure the leaf area of five randomly selected plants by destructive sampling method. The biomass produced from same five plants used in LAI measurements was dried in an oven to record the dry weight which was used for the measurement of the crop growth rate (CGR) at 30 days interval. Sampling for CGR was started at 60 DAS. The CGR and net assimilation rate (NAR) was determined following Hunt (1978) as detailed in equation 1 and 2.

$$\mathrm{CGR} = \frac{W_2 - W_1}{t_2 - t_1} \quad \text{(Eq. 1)}$$

Where W_1 is the total dry weight per unit land area at the first harvest and W_2 is the total dry weight per unit land area at the second harvest; t_1 is the time taken to the first harvest and t_2 is the time taken to the second harvest.

$$\mathrm{NAR} = \frac{\text{Total dry matter}}{\text{Leaf area duration}} \quad \text{(Eq. 2)}$$

Number of Bolls Per Plant, Biomass Production and Harvest Index of *Bt* Cotton

In each year, the total number of bolls of all tagged plants were counted periodically (fortnight intervals) and averaged. The total aboveground plant parts from each plot were cut at the final picking, sundried for a week, weighed to determine the biomass production (kg ha^{-1}). The abscised leaves were collected at regular intervals and they were also included for estimation of biomass production. Harvest index was computed by dividing seed cotton yield to biomass production and expressed in percentage.

Fiber Quality

Lint samples obtained after ginning clean seed cotton were used to estimate the fiber quality parameters. The lint was initially conditioned at 65% R.H. and 18–20°C in an air-conditioned chamber, using humidifier. Fiber fineness (µg tex^{-1}), fiber uniformity (%), fiber strength (g tex^{-1}), fiber length (mm) and fiber elongation (cm) were determined following Moore (1996), using High Volume Instrument (HIV 900SA; Zelwiger, Uster, U.K.).

Statistical Analysis

The collected data were tested for normality first, and the parameters having non-normal distribution were normalized by Arcsine transformation. The difference among years was tested by paired t test, which indicated significant difference. Therefore, the data of both years were analyzed separately. The data of the parameters where year effect was non-significant were pooled instead of analyzing separately. Two-way analysis of variance (ANOVA) was then used to test the significance in the data. Least significant difference test at 5% probability level was the used to separate treatments' means where ANOVA indicated significance (Steel *et al*., 1997).

Results

Different cropping system treatments, locations and interaction among them had significantly influenced the allometric traits of *Bt* cotton (Table 3). Among cropping systems, CT cotton planted in early March at fallow land presented the highest crop growth rate (CGR), leaf area index (LAI) and net assimilation rate (NAR), being followed by cotton intercropped in BSW in early March (Fig. 1). The lowest CGR, LAI and NAR were found in cotton sowing on CT field during late April, after harvesting of FSW (Fig. 1).

The CT cotton crop sown in early March after fallow land produced the highest number of bolls per plants (Fig. 2). On the other hand, CT cotton crop planted in late April after harvesting FSW had the lowest boll production per plant (Fig. 2). Higher NAR, LAI and CGR was recorded in Vehari than Multan (Fig. 1).

The biomass production, plant height, number of bolls per plant and harvest index were significantly influenced by different locations and cropping systems (Table 3). In Vehari, CT cotton crop sown in early March after fallow land had the tallest plants and caused the highest biomass production in 2013 (Table 4). For plant height and biomass production, the cotton crop performed better in Vehari than Multan (Table 4). In both years, the lowest plant height and biomass production were found in the CT cotton sown after harvesting FSW in late April in Multan (Table 4). The relay-intercropping of cotton in ridge-sown wheat in late March recorded the highest harvest index, followed by relay-intercropping of cotton in ridge-sown wheat in early March, in Multan 2012. The lowest harvest index was recorded when the CT cotton was sown after harvesting FSW in late April either in Multan or Vehari in 2013 (Table 4).

Different fiber quality traits of Bt cotton were significantly altered by different locations and cropping systems (Table 3). The CT cotton crop sown after harvesting FSW in late April reduced fiber quality, with plants showing the lowest fiber fineness, fiber uniformity and fiber length (Figure 3a–c). The fiber elongation and fiber strength were increased in CT crop sown on fallow land in early March in Vehari (Fig. 3). Fiber firmness, fiber uniformity, fiber length and fiber strength were improved in the relay-intercropping of *Bt* cotton in BSW in early March as compared to CT cotton sown after FSW harvest in late April (Fig. 3a–e).

Table 3: Statistical summary of growth, biomass production and fiber quality parameters of cotton sown under varying locations and cropping systems

Response variables	Year-I			Year-II		
	Locations (L)	Cropping systems (S)	L × S	Locations (L)	Cropping systems (S)	L × S
Leaf area index	**	**	NS	**	**	NS
Crop growth rate	**	**	NS	**	**	NS
Net assimilation rate	**	**	**	**	**	NS
Plant height	**	**	**	**	**	*
Biomass production	**	**	**	**	**	NS
Harvest index	*	**	**	**	*	NS
Number of bolls per plant	**	**	NS	**	**	NS
Fiber fineness	**	**	NS	**	**	**
Fiber uniformity	**	**	NS	**	**	**
Fiber length	NS	**	NS	NS	**	*
Fiber elongation	**	**	NS	NS	**	NS
Fiber strength	**	**	**	**	**	NS

** = Significant at p 0.01; NS = Non-significant

Table 4: Plant height, biomass production and harvest index of *Bt* cotton under different Bt-CWCS at two locations

Treatments	Plant height (cm)				Biomass production (kg ha^{-1})				Harvest Index (%)			
	2012		2013		2012		2013		2012		2013	
	Multan	Vehari	Multan	Vehari	Multan	Vehari	Multan	Vehari	Multan	Vehari	Multan	Vehari
CT cotton sown in early March after fallow land	146.5 d-h	150.4 bcd	153.9 ab	157.1 a	11239 c-g	12470 ab	12068 a-d	12794 a	31.80 a-d	29.80 c-f	31.28 a-e	30.48 b-f
CT cotton sown in late March after fallow land	143.7 g-k	150.1 b-e	152.0 bc	153.9 ab	10485 g-l	11718 be	11203 d-h	11208 c-h	32.20 abc	29.28 def	29.54 def	30.82 a-f
CT cotton sown after FSW harvest in late April	136.5 m	139.5 lm	137.4 m	140.1 klm	8850 p	9661 l-p	9129 op	9580 m-p	31.00 a-f	31.56 a-e	28.58 f	29.03 ef
Cotton intercropping in BSW in early March	142.0 i-l	144.1 f-k	146.3 d-h	150.1 be	10285 i-m	11464 c-f	11433 c-f	12086 abc	31.22 a-e	29.36 def	30.78 a-f	29.58 def
Cotton intercropping in BSW in late March	137.6 m	146.2 e-h	144.9 f-i	149.9 be	9788 k-o	10776 f-j	10335 h-m	10671 f-j	31.16 a-f	29.46 def	29.52 def	29.54 def
Cotton intercropping in RSW in early March	140.4 j-m	144.2 f-k	144.3 f-j	147.9 c-f	10107 i-n	10973 e-i	10603 f-k	10718 f-j	33.04 ab	31.09 a-f	30.48 b-f	31.32 a-e
Cotton intercropping in RSW in late March	139.4 lm	147.7 d-g	143.0 h-l	146.2 e-h	9356 nop	10438 g-m	10050 j-n	10165 i-n	33.12 a	30.38 c-f	29.49	30.99 a-f
LSD value (p 0.05)	4.11				882.3				2.61			

Means sharing the same letter, within a column, do not differ significantly at *P* 0.05
CT = Conventionally tilled; FSW = Flat sown wheat, BSW = Bed sown wheat and RSW = Ridge sown wheat; CWCS = Cotton-wheat cropping system

Discussion

The allometry and quality of cotton was significantly influenced by different cropping system treatments included in the study. As hypothesized, relay intercropping significantly improved the allometry, yield and quality of cotton. These improvements could be directly linked to the availability of longer growth period to Bt cotton, which helped it to attain the higher yield and quality. Moreover, the high yield and quality of relay-intercropped cotton indicated it as a promising agronomic option to improve the yield and quality of Bt cotton in cotton-based cropping systems.

Induction of *Bt* cotton in cotton-wheat cropping systems may increase the overall system productivity. However, wheat may be compromised due to the longer cycle of *Bt* cotton as compared to conventional cotton. Herein, we presented inter-/relay cropping of *Bt* cotton in wheat field as an alternative to manage time conflict between these two crops. Although relay intercropping caused interspecific competition, the performance of relay-intercropped *Bt* cotton in terms of crop allometry and fiber quality was better than the CT cotton crop sown after harvesting FSW in late April (Fig. 1 and 3).

The crop cycle of CT cotton on fallow land and relay intercropped cotton in bed- or ridge-sown wheat was similar due to the same sowing date. As consequence of lower competition for moisture, nutrients and solar radiation for 6–8 weeks, CT cotton on fallow land performed better than the relay-intercropping of cotton. Indeed, the crop plants grown together compete each other for resources (Wang *et al.*, 2005), which ultimately effects the survival, growth or reproductive phase of the one or both crops (Crawley, 1997). Although, the component crops in intercropping might face yield penalty (Khan *et al.*, 2012); however, the net returns per unit area are higher in intercropping (Zhang *et al.*, 2007; Shah *et al.*, 2016; Hussain *et al.*, 2017).

The NAR was the lowest from 91–120 days after sowing. Indeed, crop phenology is affected by temperature through its effects on development and growth (Hussain *et al.*, 2012b). The optimum growth of cotton occurs at 30°C and growth decreases quickly when crop is exposed to extended period of 40°C (Hodges *et al.*, 1993). This increase in temperature might have lowered NAR in cotton.

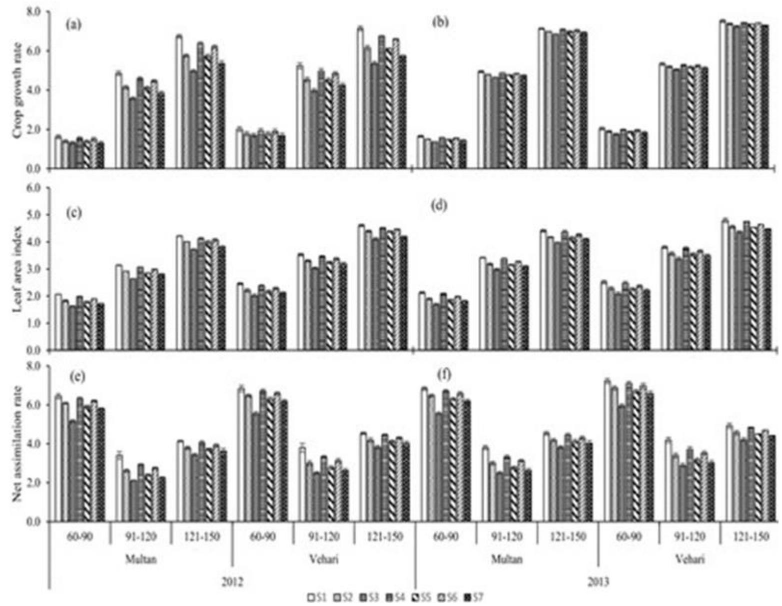

Fig. 1: Crop growth rate (g m^{-2} day^{-1} in a, b), leaf area index (in c, d) and net assimilation rate (g m^{-2} day^{-1} in e, f) of cotton plants in *Bt* cotton-wheat cropping systems in Multan and Vehari, Pakistan, during 2012 (a, c, e) and 2013 (b, d, f)
S_1 = conventionally tilled cotton sown in early March after fallow land; S_2 = conventionally tilled cotton sown in late March after fallow land; S_3 = conventionally tilled cotton sown after flat-sown wheat harvest in late April; S_4 = cotton intercropping in bed-sown wheat in early March; S_5 = cotton intercropping in bed-sown wheat in late March; S_6 = cotton intercropping in ridge-sown wheat in early March; S_7 = cotton intercropping in ridge-sown wheat in late March. Each histogram is mean value of 3 replications ± S.E

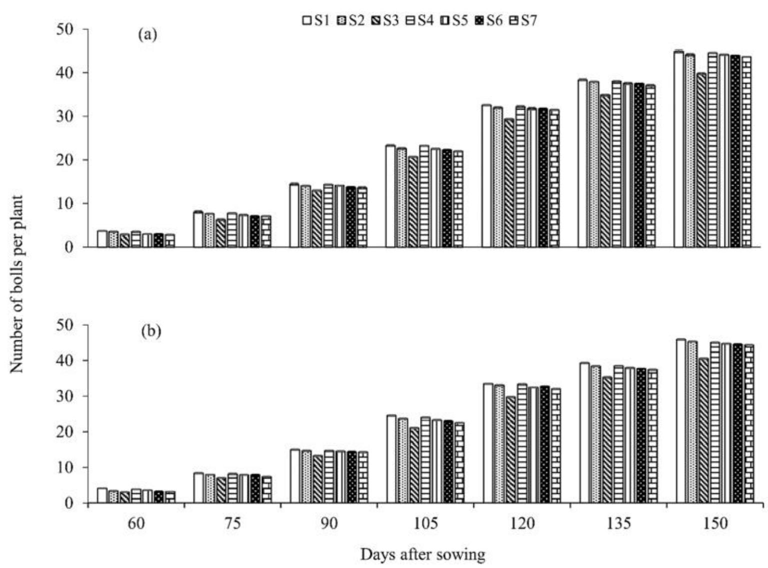

Fig. 2: Number of cotton bolls per plant in *Bt* cotton-wheat cropping systems in Multan (**a**) and Vehari (**b**), Pakistan
S_1 = conventionally tilled cotton sown in early March after fallow land; S_2 = conventionally tilled cotton sown in late March after fallow land; S_3 = conventionally tilled cotton sown after flat-sown wheat harvest in late April; S_4 = cotton intercropping in bed-sown wheat in early March; S_5 = cotton intercropping in bed-sown wheat in late March; S_6 = cotton intercropping in ridge-sown wheat in early March; S_7 = cotton intercropping in ridge-sown wheat in late March. Each histogram is mean value of 3 replications ± S.E

The CGR and biomass accumulation by a crop are determined by the NAR and LAI (Hunt, 1978). In this study, the highest CGR, NAR and LAI were recorded when CT cotton was sown on fallow land in early March, which was translated into taller plants, more bolls per plant, biomass production and harvest index (Fig. 1, 2 and Table 2). Initially growth stunting was noted in relay-intercropped cotton due to less light capture caused by shading. After the wheat harvest, cotton extended canopy and roofed the existing space to enhance the sunlight exploitation capacity earlier than the CT cotton crop which was sown after harvesting the flat sown wheat in late April. In an earlier study, Arshad *et al.* (2007) found that that early sowing produced higher seed cotton yield and ginning out turn than

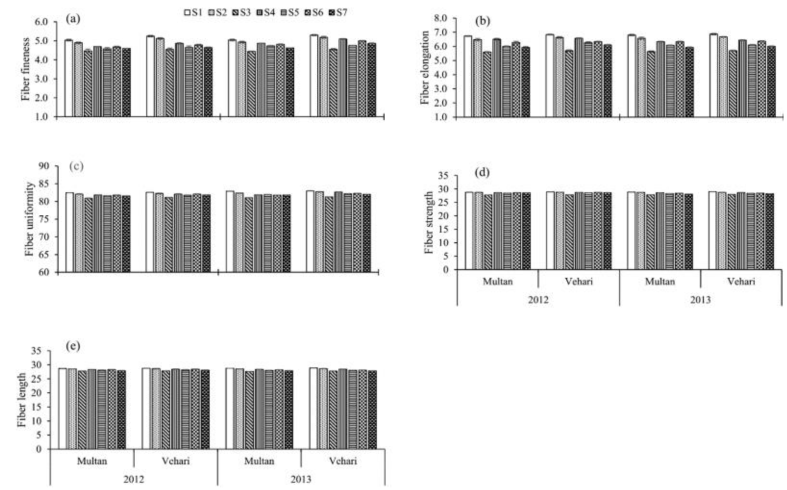

Fig. 3: Fiber fineness (μg inch^{-1}, in **a**), fiber elongation (cm, in **b**), fiber uniformity (%, in **c**), fiber strength (g tex^{-1}, in **d**) and fiber length (mm, in **e**) of *Bt* cotton-wheat cropping systems in Multan and Vehari, Pakistan

S_1 = conventionally tilled cotton sown in early March after fallow land; S_2 = conventionally tilled cotton sown in late March after fallow land; S_3 = conventionally tilled cotton sown after flat-sown wheat harvest in late April; S_4 = cotton intercropping in bed-sown wheat in early March; S_5 = cotton intercropping in bed-sown wheat in late March; S_6 = cotton intercropping in ridge-sown wheat in early March; S_7 = cotton intercropping in ridge-sown wheat in late March. Each histogram is mean value of 3 replications ± S.E

the late sown cotton crop.

Although, the fiber quality of cotton is a genetically controlled factor; nonetheless, the environment and growth conditions may influence fiber quality to a certain extent (Awan *et al.,* 2011; Fig. 3). The fiber quality of CT cotton crop sown on fallow land in early/late March was better than other treatments which were visible through improvement in fiber strength, fiber length, fiber uniformity and fiber elongation (Fig. 3). However, fiber quality of relay-intercropped cotton was also better than late sown CT cotton after wheat harvest. This improvement in fiber quality might be due to higher maturity of fiber in case of early planting compared with late planted cotton in the respective treatments (Hallikeri *et al.,* 2009). Some people concluded that late planting of cotton usually results in decline in seed cotton yield and fiber quality due to a shortened fruiting period and delayed maturity as compared to normal planting (Awan *et al.,* 2011; Shah *et al.,* 2017, 2019). Therefore, the relay intercropping of Bt cotton in the wheat (flat and bed sown wheat) may be helpful in improving the growth and fiber quality of *Bt* cotton in this system.

Conclusion

The relay-intercropping of *Bt* cotton in bed or ridge-sown wheat during early March showed better growth, biomass production along with better quality fiber than CT *Bt* cotton sown after harvest of wheat sown on flat land during late April in cotton-wheat cropping systems in Pakistan. Thus, the inter-/relay cropping of *Bt* cotton in wheat field may serve as an alternate to manage time conflict between these two crops which occur due to sowing of CT cotton crop after harvesting flat-sown wheat in late April.

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