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Original Article

Assessing critical period of weed competition in direct seeded rice (*Oryza sativa* L.)

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Abstract

In the present era, direct-seeding is a viable alternative of traditional transplanting of rice for farmers due to water and labour shortage. It has the potential to ensure water and labour saving along with higher productivity of water. Study was performed to assess the critical period of weed-crop competition i.e. time period during which weeds cause maximum reduction of yield in dry direct-seeded basmati rice during two consecutive summer seasons of the years 2015 and 2016. This experiment consisted of 6 weed competition periods [0, 2, 3, 4, and 5 weeks after crop emergence (WAE)] and 6 weed-free periods (0, 2, 3, 4, and 5 WAE) by mixed weed flora. The experiment was executed in randomized complete block design having four replications. With the increasing duration of the weed-crop competition, the productive tillers, grains per panicle, and 1000-grain weight were decreased gradually. A whole season competition with mixed weed flora reduced rice grain yield up to 90% and increased N, P, and K uptake by weeds up to 28, 5, and 28 kg ha^{-1}, respectively. In dry direct-sown rice, the critical time of weed removal as estimated by the three-parameter logistic model was 1.4-6.3 WAE and 2.8-4.8 WAE to save 10 and 20% grain yield, respectively. Hence it is concluded that dry direct-seeded rice crop should be kept weed free during this time period of crop growing season.

Keywords: Direct-seeded rice, weed-crop competition, critical time, yield.

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Introduction

A period during a crop growth duration when the weed infestation is utmost harmful compared to the rest of growing season having a little or no impact, and when weed competition with crop results insubstantial loss in crop yields is called critical weed competition period. The concept of the crop-weed competition was firstly given by Nieto et al. (1968) as the period during which the weeds exert a significant effect on crop yield and beyond this critical period, weeds exert a negligible impact on crop yields. However, this concept was explained by Zimdahl (1999) as a growth period assessed empirically during which crop yield is minimized to the greatest extent due to weed competition. These critical periods are un-static and depend upon weed species, climate, soil, crop variety as well as on the crop production technology being practiced. During this period, control of weeds should be done to avoid unbearable losses to crop yield (Azmi et al., 2007). Usually, critical weed-crop competition period exists in an annual crop during the first one-third to one-half of its life cycle (Mercado, 1979). A time period during which the weed existence can cause a significant decline in crop yield is termed as critical period of weed competition as mentioned by Nazarko et al. (2005)., An estimate of critical weed competition period acts as a tool for deciding the most suitable timing of weed control in any crop (Knezevic et al., 2002). The growt and yield of direct-seed rice (DSR) crop is mainly hampered by weeds due to their aggressive growth that may cause its grain yield loss between 60% to 100% (Rao and Nagamani, 2007). The critical period of weed-crop competition in DSR depends mainly on soil moisture conditions at the time of crop sowing as 15-60 DAS in wet-DSR Mukherjee et al., 2008); 15-45 DAS in dry-DSR (Rao and Nagamani, 2007; Yaduraju and Mishra, 2004), first 30 DAS in upland rice conditions (Ladu and Singh, 2006) and up to 45 DAS in drilled-DSR (Naidu and Bhan, 1980). So the DSR crop must be sustained weed-free throughout these critical periods to gain a yield equivalent to the weed-free conditions (Johnson et al., 2004).

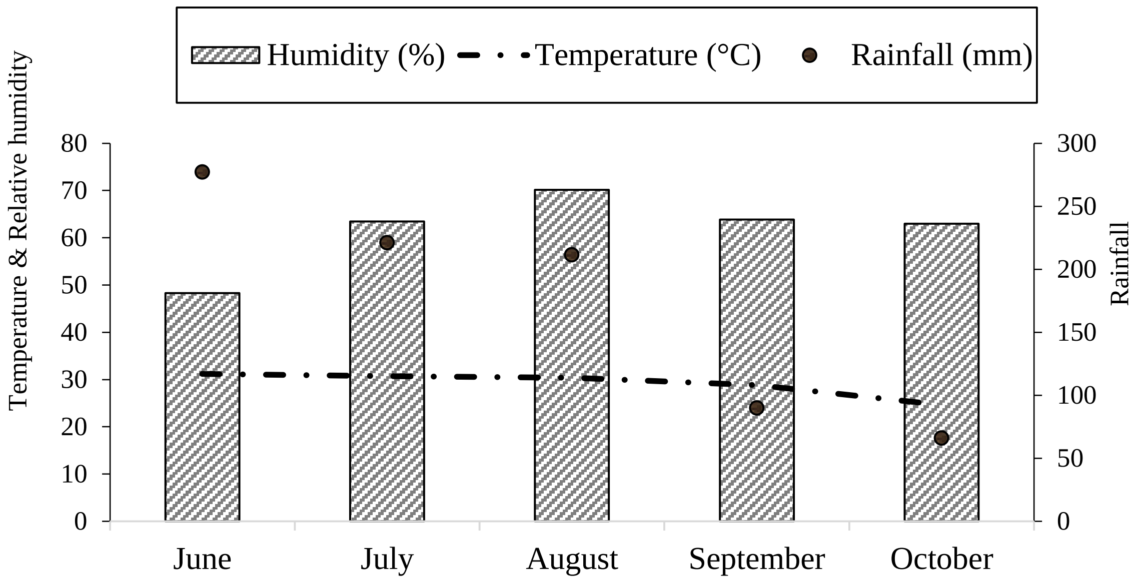
One of the important features of the grassy weeds competing with the DSR is that these have C_4 pathway of photosynthesis (Caton et al., 2004) due to which weeds have a competitive advantage on rice that has a C_3 pathway of CO_2-fixation. The critical periods regarding weed-crop competition in different rice sowing techniques are summarized by Arunbabu and Jena (2018). Under Indian conditions, the critical weed competition period of wet direct-seeded rice is 15-60 DAS as compared to 20-40 days after transplanting (DAT) in transplanted rice (Mukherjee et al., 2008) Moreover, rice grain yield losses are comparatively higher in dry direct-seeded rice than wet direct-seeded rice (Singh, 2008) However, under Pakistani conditions, the period between 20-50 DAS was proved to be more critical when three cultivars of fine rice viz., Shaheen-Basmati, Super-Basmati and Basmati-2000 were sown by direct seeding method (Khaliq and Matloob, 2011). Johnson et al. (2004) demonstrated that critical periods of weed-crop competition was between 29-32 DAS and 4-83 DAS in wet-DSR and dry-DSR, respectively to achieve 95% weed-free crop yields. Similarly, a loss in the aerobic rice yield ranged from 47-66 kg ha^{-1} day^{-1} when the weeds thrived between 14-56 DAS in dry-DSR (Chauhan and Johnson, 2011) while 30-40 DAS was found to be the most crucial time regarding weed eradication. However, Prashanthi et al. (2017) specified the critical periods of weed-crop competition as between 20-40 DAS. The crop sown by narrow spacing increased its capability to compete with weeds more efficiently (Kristensen et al., 2008), and this enhanced competitiveness minimized the period of weed-crop competition (Chauhan and Johnson, 2011).

In direct-sown rice at Sahel West Africa, the critical periods of the weeds, to get a 95% weed-free rice grain yield was predicted to be 29-30 DAS and 4-83 DAS during wet and dry sowing seasons, respectively (Johnson et al., 2004). Juraimi et al. (2013) reported these critical periods in DSR in un-saturated conditions as 2-71 DAS and 5-52 DAS, respectively at a 5 and 10% yield loss, while these periods for DSR in saturated field conditions were estimated to be 15-73 as well as 25-51 DAS at 5% and 10% yield loss. Azmi et al. (2007) predicted the critical period to control the weedy rice at 5% yield loss as 16-53 DAS when the analysis was performed by applying logistic and Gompertz response curve while Begum et al. (2008) found these critical periods for grass-like fimbry as between 14-28 DAS based on logistic and Gompertz response curve. Anwar et al. (2012) noted these critical periods during the off-season and on-season as 7-49 DAS and 7-53 DAS, respectively to get a 95% weed-free paddy yield, while these periods were 23-40 DAS and 21-43 DAS during the off-season as well as main-seasons, respectively to get a 90% weed-free paddy yield in the direct-sown AERON-1 rice cultivar. As weed control is of utmost importance in DSR, it is necessary to launch an efficient weed control program based on accurate knowledge of critical weed competition period in DSR. Therefore, studies were proposed to estimate critical competition period of weeds in DSR under semi-arid conditions of Sargodha.

Material and Methods

Experimental site and soil

During the two summers of consecutive years 2015 and 2016, a field trial was held at the Agronomic research area (Latitude 32.13 °N, longitude 72.68 °E and altitude 189 m) of the Department of Agronomy, College of Agriculture, University of Sargodha, Punjab-Pakistan. The soil of the research site belongs to the Sargodha soil series (fine silty, mixed hyper-thermic, sodic soils). The physio-chemical investigation of soil was carried out before crop sowing each year (Table 1). The meteorological data of the experimental site for growing seasons of two years was collected from the Agricultural Meteorology Cell (In-service Training Institute Sargodha, Pakistan) located in the vicinity of the research site (Figure 1).



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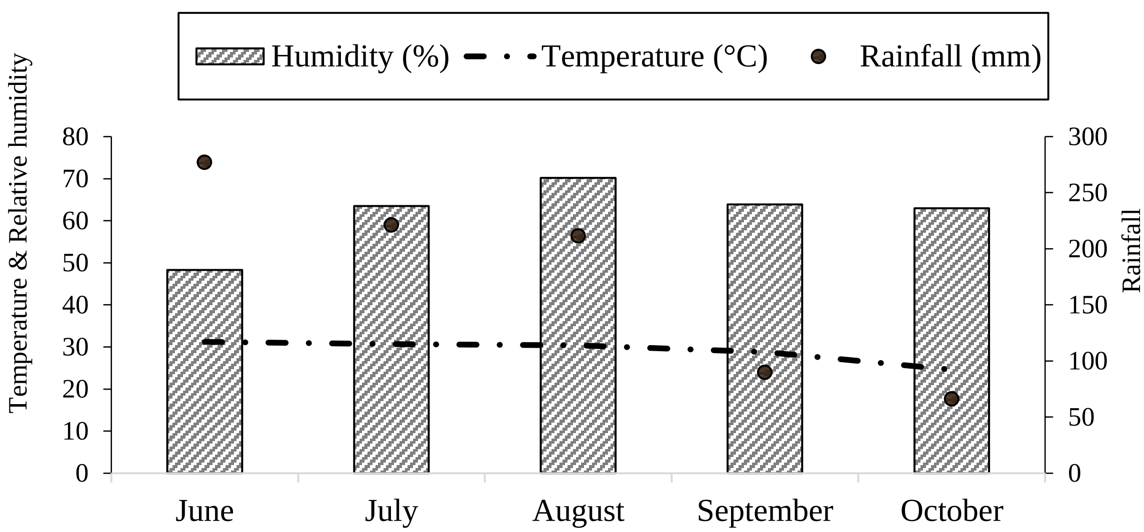


Figure-1. Meteorological data of experimental site for growing seasons (a) 2015 and (b) 2016

Table-1. Physico-chemical analysis of site soil, College of Agriculture (COA), Sargodha, Pakistan.

Features	Units	Soil properties at two soil depths					
		2015			2016		
		15 cm	30 cm	Mean	15 cm	30 cm	Mean
Soil pH	-	7.7	7.8	7.75	7.8	7.9	7.85
EC	dS m^{-1}	1.73	1.80	1.76	1.76	1.79	1.77
Organic matter	%	0.90	0.55	0.72	0.93	0.53	0.73
Total Nitrogen	%	0.04	0.03	0.04	0.04	0.04	0.04
Available P	ppm	8.4	4.1	6.25	8.5	4.2	6.35
Available K	ppm	162	148	155	165	155	160
Texture	-	Loam			Loam		

Experimentation and growing conditions

The rice crop was sown on the 4^{th} of June in 2015 and the 7^{th} of June in 2016. The soil was laser leveled to make it flat. A finely pulverized seedbed was prepared by plowing 2 to 3 times during both the years by a tractor-driven cultivator with subsequent plankings. Super-basmati, a fine rice variety, was utilized as an investigational crop. The crop was sown on a well pulverized flat seedbed in lines having a distance of 25 cm by hand drill with a seed rate of 35 kg ha^{-1}. Nitrogen, phosphorus, and potash were applied at 135, 75, and 60 kg ha^{-1} as urea, di-ammonium phosphate and sulfate of potash, respectively. By one-third of nitrogen with entire P_2O_5 and K_2O were utilized at final seedbed preparation. The rest of one-third of the nitrogen was broadcasted at tillering stage (30 DAS), while one-third was at panicle commencement (65 DAS). As crop protection measures, insecticide Stark 4G (Cartape-hydrochloride) was utilized at 880 g of its a.i. ha^{-1} to control rice borers at 25 DAS, insecticide Karate 5EC (lambda-cyhalothrin) was used twice as a foliar application by hollow cone nozzle in the middle of August to control rice leaf folder at 31g of its a.i. ha^{-1}. A foliar application of fungicide Topsin-M 70WP (Thiophanate-methyl) at 700 g of its a.i. ha^{-1} was made by hollow cone nozzle in the last week of September as a preventive measure against paddy blast.

A hand drill was employed for crop sowing in 25 cm apart rows. The dimension of the net plot size was 6.0 m × 3.0 m . The experimental treatments comprised of 6 weed competition periods [0, 2, 3, 4, and 5 weeks after crop emergence (WAE)] and 6 weed-free periods (0, 2, 3, 4, and 5 WAE) by mixed weed flora. The dominant weeds present at experimental field were jungle rice (*Echinocloa colona*), false amaranth (*Digera arvensis*), field bindweed (*Convolus arvensis*), parthenium (*Parthenium hysterophorus* L.), mukia (*Mukia maderaspatana* L. M. Roem), johnson grass (*Sorghum halepense* L.), southern crabgrass (*Digitaria ciliaris*), chinese sprangletop (*Leptochloa chinensis*), creeping panic grass (*Echinochloa reptans* L. Roberty), devil's weed (*Tribulus terrestris* L.), variable flatsedge (*Cyperus difformis*) and rice flatsedge (*C. iria*). All the weeds were uprooted from the whole plot after/before the prescribed competition duration according to treatment plan. In no weed competition treatment (control), the weed seedlings were uprooted right after their germination, while in treatment having whole season weed competition, no weed was eradicated during the entire crop growth season. The research trial was designed in a randomized complete block design with 4 replications. All other agronomic practices and crop protection measures were kept uniform, excluding those under study.

Statistical analysis

Three-parameter logistic equation was employed to explain the impact of an ever-increasing time regarding weed infestation on paddy relevant yield. A separate analysis of year-based data was executed as there was a different environmental condition for two years. The parameters related to non-linear regression were evaluated by iteratively employing the NLIN Procedure of SAS according to the method as proposed by Knezevic et al. (2002) given in equation 1.

$$Y = ((1/(EXP(K * (T - X)) + F)) + ((F - 1)/F)) \times 100$$
(Equation 1)

Whereas; Y represents the rational paddy yield (% whole season weed-free control), T reveals the time duration pronounced as days after crop emergence (DAE), while X presents the deflection point (DAT), whereas; K and F are constants (Knezevic et al., 2002).

Results and Discussion

Weed growth

The fresh and dry weight of mixed weed flora was increased significantly by the increase in the weed-crop competition periods (WCCP). The lowest fresh weight (242.3 & 263.2 kg ha^{-1}) and dry weight (66.5 & 73.2 kg ha^{-1}) of the weeds was noted in treatments with weed-crop competition for 2 WAE in the first and second year, respectively that were significantly increased as WCCP was increased (Table 2). Consequently, a weed competition for full growing season of crop resulted in the highest fresh weight (2881.7 & 2881.1 kg ha^{-1}) and dry weight (692.9 & 779.2 kg ha^{-1}) of weed for the two years, respectively. The different contrasts arranged between various treatments were found to be significant for both of the years. The increased fresh weight of weed by increasing the weed-crop competition periods might be due to the expansion in the growth duration of weeds ultimately resulting in more weed biomass accumulation. An increase in the weed biomass due to an extension in the weed-crop competition duration in garden cress was also stated by Rehman et al. (2020a, b). Rehman et al. (2019) recorded a higher weed fresh weight by an increase in the competition periods of naturally occurring weeds in wheat. Safdar et al. (2016)and Bajwa et al. (2020a, b) concluded that by increasing competition periods of *Parthenium hysterophorus* in maize, sorghum and direct-seeded rice, the weed biomass was also increased significantly. Rehman et al. (2020a, b) also pointed out that an extended weed-crop competition duration increased the weed fresh weight in maize. An increase in weed's dry weight due to the increased WCCP might be due to an increase in fresh weight of weed. Our research outcomes are consistent with Khaliq and Matloob (2011) who stated a steady incline in weed dry weight at each succeeding competition period in DSR.

Table-2. Weed fresh and dry weights (kg ha^{-1}) of different weed-crop competition periods under DSR

	Fresh weight		Dry weight	
Treatments	**2015**	**2016**	**2015**	**2016**
Weed-crop competition periods (weeks)				
No weed competition (control)	-----	-----	-----	-----
2	242.3 f	263.2 f	66.5 f	73.2 f
3	591.0 e	604.9 e	160.1 e	161.3 e
4	936.9 d	957.4 d	253.2 d	245.0 d
5	1329.9 c	1350.7 c	332.3 c	347.0 c
Weed-free periods (weeks)				
5	608.6 e	628.8 e	154.2 e	161.5 e
4	828.1 d	858.6 d	200.3 de	226.9 d
3	1318.4 c	1313.3 c	338.2 c	345.5 c
2	1671.3 b	1695.9 b	430.4 b	424.9 b
Full season weed competition (check)	2881.7 a	2888.1 a	692.9 a	779.2 a
Contrast comparison				
Competition for 2 WAE Vs competition for (3 + 4) WAE	242 vs 764**	263vs 81**	66 vs 206**	73 vs 203**
Competition for 3 WAE Vs competition for (4 + 5) WAE	591vs1133**	604vs 54**	160vs292**	161vs296**
Weed-free for 5 WAE Vs weed-free for (4 + 3) WAE	608 vs 1085**	628vs1085**	154 vs 286**	161 vs 286**
Weed-free for 4 WAE Vs weed-free for (3 + 2) WAE	828 vs1504**	858 vs 1504**	200 vs 385**	226 vs 385**

Based on the least significant difference (LSD) test, the mean values in a column with different letters are substantially different (P < 0.05) from one another; ** indicates significant at P < 0.01

Table-3. NPK contents (%) and NPK uptakes (kg ha^{-1}) of weeds by different weed-crop competition periods under DSR

Treatments	N uptake		P uptake		K uptake	
	2015	2016	2015	2016	2015	2016
Weed-crop competition periods (weeks)						
No weed competition (control)	-----	-----	-----	-----	-----	-----
2	1.91 f	2.12 f	0.24 f	0.28 f	1.9 f	2.1 f
3	4.94 e	5.00 e	0.72 e	0.76 e	4.8 e	4.8 e
4	8.00 d	7.77 d	1.30 d	1.30 d	7.8 d	7.6 d
5	10.76 c	11.26 c	1.92 c	2.06 c	10.5 c	11.0 c
Weed-free periods (weeks)						
5	4.76 e	5.02 e	0.70 e	0.75 e	4.7 e	4.9 e
4	6.37 de	7.24 de	1.04 de	1.21 d	6.2 de	7.2 d
3	11.0 c	11.4 c	1.96 c	2.04 c	10.9 c	11.2 c
2	14.4 b	14.3 b	2.80 b	2.84 b	14.3 b	14.2 b
Full season weed competition (check)	24.4 a	27.7 a	4.80 a	5.46 a	24.3 a	27.6 a
Contrast comparison						
Competition for 2 WAE **Vs** (3 + 4) WAE	1.91 vs 6.47**	2.12 vs 6.39**	0.24 vs 1.01**	0.28 vs 1.03**	1.91 vs 6.35**	2.11 vs 6.25**
Competition for 3 WAE **Vs** (4 + 5) WAE	4.94 vs 9.38**	5.00 vs 9.52**	0.72 vs 1.61**	0.76 vs 1.68**	4.80 vs 9.21**	4.85 vs 9.36**
Weed-free for 5 WAE **Vs** (4 + 3) WAE	4.76 vs 9.32**	5.02 vs 9.32**	0.70 vs 1.63**	0.75 vs 1.63**	4.72 vs 9.22**	4.97 vs 9.22**
Weed-free for 4 WAE **Vs** (3 + 2) WAE	6.37 vs 12.88**	7.24 vs 12.88**	1.04 vs 2.44**	1.21 vs 2.44**	6.29 vs 12.76**	7.21 vs 12.76**
Weed-free for 3 WAE **Vs** (2 WAE + Full season weed competition)	11.00 vs 21.07**	11.40 vs 21.07**	1.96 vs 4.15**	2.04 vs 4.15**	10.90 vs 20.98**	11.24 vs 20.98**

Based on the least significant difference (LSD) test, the mean values in a column with different letters are substantially different ($P < 0.05$) from one another; ** indicates significant at $P < 0.01$

Weed NPK uptakes (kg ha^{-1})

Weed NPK uptake were significantly affected by the increasing WCCP. Significantly the lowest weeds NPK uptakes (1.91, 0.24 & 1.9 kg ha^{-1} for the first and 2.12, 0.28 & 2.1 kg ha^{-1}, respectively for the second year was recorded in plots with WCCP for 2 WAE that were significantly and gradually enhanced as weed competition duration was increased. Consequently, the highest NPK uptakes (24.4 and 27.7, 4.80 and 5.46, & 24.3 and 27.6 kg ha^{-1}, respectively) were recorded under whole season competition between rice and weeds. Different contrasts formulated within different treatments revealed that NPK uptake differed significantly among competition periods for 2 weeks vs (3+4) weeks, 3 weeks vs (4+5) weeks, weed-free for 5 weeks of crop emergence vs (4+3) weed-free weeks, weed-free for 4 weeks of crop emergence vs (3+2) weeks weed-free periods as well as weed-free for 3 weeks of crop emergence vs 2 weeks weed-free of crop emergence + full season (Table 3). The increase in the weed's NPK uptake with the increased WCCP might be due to a consequence of a greater weed plant biomass storage with an increase in their growth durations. Mehmood (2015) stated the highest weeds NPK uptake in treatment with full-season weed competition in the transplanted rice. These research findings are further reinforced by Anjum et al. (2007) as well as Rehman et al. (2017) and Ikram et al. (2012) who also recorded an increased weed NPK uptake in the weedy-check treatments.

Rice crop growth

The plant height at maturity is an overall result of its vegetative growth and it also reveals the extent of crop-weed competition. The rice plant height was significantly influenced by various WCCP. The highest plant height of rice (84.9 & 89.2 cm) in the first and second year, respectively was noted with control plots (Table 4). The rice plant height was gradually decreased as the duration of WCCP was increased and a minimum plant height of rice (54.8 & 59.2 cm in 2015 and 2016, respectively) was noted in plots with a WCCP for a full season. The contrasts established between the diverse treatments were proved as statistically significant for the two years. The plant height of rice decreased significantly under an increased weed-crop competition duration due to intense inter-specific competition among weed and crop for longer period of crop vegetative growth. Mehmood (2015) reported the highest rice plant height (113.7 cm) in control treatments, while the lowest (104.8 cm) in the weedy-check treatments. These conclusions were further reinforced by Begum (2006) who pointed-out a significant decline in the plant height of DSR when a WCCP was established with *Fimbristylis miliacea* for 70 DAE. Begum et al. (2008) identified the higher plant height of rice in plots having no weed-crop competition in DSR. Our research findings are also analogous to that of Chauhan and Johnson (2010) who also reported a decline in the rice plant height when DSR was subjected to competition with the increasing density of *E. colona*.

Panicle length is an important agronomic trait that is essential for determining rice yield and it is fundamentally a genetically governed factor; however, it may be affected by prevailing ecological conditions to some extent. A gradual decline in the panicle length of rice was observed as the weed-crop competition duration was prolonged. The plots with no weed-crop competition resulted in the maximum panicle length of rice (24.5 & 25.9 cm in 2015 and 2016, respectively) and this treatment was proved to be at par with 2 weeks WCCP after the crop emergence (Table 4). Contrastingly, the minimum panicle length of rice (17.4cm for the first year & 17.8cm for the second year) was attained in plots with a full-season WCCP. The contrast comparisons between different treatments having various WCCP were found to be significant for the two years. A gradual decline in the panicle length of rice with an increased weed-crop competition duration might probably be due to a gradual increase in inter-specific weed-crop competitiveness for similar growth resources. These outcomes are validated by Mehmood (2015) who found maximum panicle length of rice (27.4 cm) in weed-free treatments, while a minimum (23.9 cm) in the weedy-check in the transplanted rice.

The biological yield of DSR was significantly affected by different durations of weed-crop competition periods as well as weed-free periods. The highest biological yield of rice, 16.71 & 17.18 t ha^{-1} in the year 2015 and 2016, respectively was noted with plots with weed-free (control) conditions (Table 4). While; a significant reduction in the biological yield of rice was noted from plots with a WCCP of 2 WAE that was proved to be at par with that of the plots with the weed-free period of 5 WAE in both of the years. Subsequently, a minimum biological yield (2.3 and 2.4 t ha^{-1} in 2015 and 2016, respectively) of rice was recorded from treatments having weeds-crop competition for the whole season. The various contrasts planned between different treatment combinations were proved to be significant in both of the years. A steady decline in the biological yield of rice by an intensification in the WCCP may be attributed to a combined outcome of decreased growth of rice along with its different yield attributing traits. Our findings are matchable to the results of Mehmood (2015) who noticed a decreased biological yield of rice with the extended infestation periods of *A. philoxeroides* in the transplanted rice while a minimum biological yield of rice was noted in plots with the full-season WCCP. Abbas et al. (2010) also noted a decline in the biological yield of wheat by an increased infestation of *E. australis*.

The productivity of a crop is reflected by its harvest index (HI) to a greater extent. The HI of DSR was significantly affected by the various WCCP. The highest HI of rice (23.2% & 23.7% in 2015 and 2016, respectively) was noted in plots having zero WCCP, which was followed by the HI of rice (22.5 & 22.9%) in plots with a WCCP for 2 WAE (Table 4). Contrastingly, the lowest HI of rice (16.1 & 16.6% for two years, respectively) was recorded from plots with a full-season WCCP. A gradual decline in the HI of rice with an increase in the WCCP might be due to a more decline in its economic yield as compared to the biological yield. In contrast, comparisons arranged within the various treatment combinations, each contrast regarding the HI of rice was proved to be significant in both of the years.

Table-4. Vegetative parameters of DSR as affected by weed-crop competition periods

	Plant height (cm)		Panicle length (cm)		Biological Yield (t ha^{-1})		Harvest index (%)	
	2015	2016	2015	2016	2015	2016	2015	2016
Weed-crop competition periods (weeks)								
No weed competition (control)	84.9 a	89.2 a	24.5 a	25.9 a	16.7 a	17.1 a	23.28 a	23.79 a
2	81.0 b	85.9 b	24.0 ab	24.5 b	14.5 bc	15.0 b	22.52 b	22.98 b
3	74.1 c	78.0 d	22.7 cd	23.4 c	13.8 c	13.8 cd	22.00 b	22.20 c
4	68.0 e	71.5 e	21.5 ef	22.2 d	12.9 d	13.0 de	20.94 c	21.11 d
5	62.6 f	64.9 g	20.4 g	20.8 e	10.2 e	10.5 f	19.92 d	20.32 e
Weed-free periods (weeks)								
5	80.8 b	83.1 c	23.4 bc	23.9 bc	15.0 b	15.0 b	21.17 c	22.11 c
4	71.1 d	73.2 e	22.2 de	22.6 d	13.9 c	14.2 bc	19.78 d	20.10 e
3	66.5 e	68.1 f	20.9 fg	21.3 e	12.4 d	12.7 e	18.57 e	18.86 f
2	59.9 g	62.4 h	18.9 h	19.2 f	9.7 e	10.5 f	16.96 f	17.35 g
Full season weed competition (check)	54.8 h	59.2 i	17.4 i	17.8 g	2.3 f	2.4 g	16.14 g	16.63 g
Contrast comparison								
Competition for 2 WAE **Vs** (3 + 4) WAE	81.1 vs 71.1**	86.0 vs 74.8**	24.0 vs 22.2**	24.5 vs 22.9**	14513 vs 13385**	15015 vs 13492**	22.5 vs 21.5**	23.0 vs 21.7**
Competition for 3 WAE **Vs** (4 + 5) WAE	74.2 vs 65.3**	78.1 vs 68.2**	22.8 vs 21.0**	23.4 vs 21.6**	13820 vs 11581**	13895 vs 11824**	22.0 vs 20.4**	22.2 vs 20.7**
Weed-free for 5 WAE **Vs** (4 + 3) WAE	80.9 vs 70.7**	83.2 vs 70.7**	23.5 vs 22.0**	24.0 vs 22.0**	15012 vs 13499**	15079 vs 13499**	21.2 vs 19.5**	22.1 vs 19.5**
Weed-free for 4 WAE **Vs** (3 + 2) WAE	71.1 vs 65.3**	73.2 vs 65.3**	22.3 vs 20.3**	22.7 vs 20.3**	13989 vs 11616**	14271 vs 11616**	19.8 vs 18.1**	20.1 vs 18.1**
Weed-free for 3 WAE **Vs** (2 WAE + Full season weed competition)	66.5 vs 60.8**	68.1 vs 60.8**	20.9 vs 18.6**	21.3 vs 18.6**	12422 vs 6447**	12728 vs 6447**	18.6 vs 17.0**	18.9 vs 17.0**

Based on the least significant difference (LSD) test, the mean values in a column with different letters are substantially different ($P < 0.05$) from one another; ** indicates significant at $P < 0.01$

Rice grain yield and yield related traits

The number of productive tillers per unit area, number of grains per panicle and 1000-grain weight are fundamental features contributing positively towards the final grain yield of rice. These all parameters showed a significant gradual decline by an extension in the weed-crop competition durations. The plots with zero weed-crop competition during the entire season resulted in the maximum number of rice productive tillers (439.5 & 479.5 m^{-2}), number of grains per panicle (108.8 and 117.3) and 1000-grain weight (22.37 g and 22.71 g) for the first and second year, respectively (Table 5). Contrastingly, the minimum number of productive tillers of rice (91.7 & 96.7 m^{-2}), grains per panicle (50.20 and 17.57) and 1000-grain weight (17.57 g and 18.1 g) were noted in treatments with the full-season weed-crop competition. The different contrast comparisons regarding these parameters which were constituted among the various treatment combinations remained significant in both of the years. A significant decline in the number of productive tillers might be due to the increased weed-crop competition durations, which may be further attributed to less capability of rice to compete for nutrients, light, and other growth resources and increased crop weakness in weed infestation environment. Our research revelations are comparable with the results of Islam et al. (2003) who pointed-out the highest number of productive tillers of rice in weed-free plots. Begum (2006) also pointed out that the number of productive tillers of rice was decreased in a WCCP from 42 DAE up to full crop season. Khaliq and Matloob (2011) observed a higher number of productive tillers of rice in weed-crop competition-free plots. El-Desoki (2003) revealed a sigmoidal relation between paddy yield and weed-crop competition duration. Juraimi et al. (2009) also stated that due to an increased WCCP, the productive tillers of rice were reduced in the transplanted rice.

A decrease in the number of grains panicle^{-1} of rice by the increased intervals of weed-crop competition may be attributed to the existence of competition among rice and weeds during the stage of flowering, fertilization and especially at the time of earring. Khaliq and Matloob (2011) stated that grains panicle^{-1} of DSR was decreased linearly when WCCP was increased. Ekeleme et al. (2007) concluded a decline in the number of grains panicle^{-1} of rice when weeds-crop competition periods were increased. Najib (2009) also noted a significant decline in grains panicle^{-1} of DSR by different weed-crop competition durations. Begum et al. (2008) also pointed out that the numbers of grains panicle^{-1} of DSR were significantly reduced by various WCCP. Khaliq and Matloob (2011) also pointed out that grains panicle^{-1} of DSR were decreased significantly due to the increased WCCP.

A significant decline in the 1000-grain weight of rice may be attributed to the stress due to weed competition at the time of rice grain filling which further endorsed an adverse impact on the grain development of rice. Begum et al. (2008) described a significant impact on the 1000-grain weight of DSR due to competition by *F. miliacea*. Shultana et al. (2013) demonstrated 1000-grain weight (21.2g & 19.9g) of rice in treatments with zero weed-crop competition and a weed-crop competition for 20 days of crop emergence, respectively in DSR. Mehmood (2015) also quoted the highest 1000-grain weight (21g) of rice in control treatments while a minimum (16.6g) 1000-grain weight was noted in treatments with full-season weed-crop competition in the transplanted rice.

The rice yield decreased linearly from WCCP from zero weeks to full-season. The maximum grain yield of rice (3.8 & 4.0 t ha^{-1}) was noted from plots with no weed-crop competition during the first and second year, respectively (Table 5). The treatment with WCCP of 2 WAE followed this treatment and was at par with the treatment with weed-free periods of 5 WAE. Contrarily, the lowest rice grain yield (0.3 & 0.4 t ha^{-1}) for the first and second year, respectively was documented in un-weeded control. Contrast comparisons constructed among various weed-crop competition periods demonstrated that the grain yield of rice differed significantly among all the combinations made within different treatments. The yield reduction of rice by an extension in the weed-crop competition periods might be due to a decline in the important yield determining parameters of rice such as the number of fertile tillers m^{-2}, the number of grains panicle^{-1} and 1000-grain weight.

Tanveer et al. (2013) highlighted a stage of crop growth stage at which it was more sensitive to weed presence, is termed as its critical periods of weed-crop competition. Khaliq and Matloob (2011) reported a loss of 89% in the grain yield of DSR by weed-crop competition for a full season. Chauhan and Johnson (2011) also recorded a reduction of 24% in the grain yield of DSR by weed-crop competition of 28 DAS. Our results are comparable with that of Ekeleme et al. (2007) who also pointed out a reduction in the yield of the transplanted rice when the duration of weed-crop competition was increased. Najib (2009) also stated that different weed-crop competition durations caused a significant reduction in the paddy yield. Shultana et al. (2013) also recorded a decreased yield of rice with the increased infestation periods of weeds in the transplanted rice. Hakim et al. (2013) also noted a decreased paddy yield due to increased weeds infestation periods. Lutz (2007) also stated a significant reduction in maize grain yield by an extension in the periods of weed infestation. Mehmood (2015) described 4 WAE as a critical period of *A. philoxeroides* in the PTR. Johnson et al. (2004) registered a higher rice grain yield when the crop was kept weed-free for 38 and 32 DAS in the wet and dry-DSR, respectively.

Model analysis and estimation of critical weed competition period

The coefficients estimates to determine the effect of timing weed removal on relative paddy yield using a logistic model have been given in Table 6. The equation fitted to the data pointed out that weed competition for 1.6 weeks after emergence (WAE) and 2.9 WAE of rice resulted in a rice yield loss of 10 and 20%, respectively; and a weed-free crop period of 6.3 WAE and 4.8 WAE caused a reduction in rice of 10 and 20%, respectively for the first year (Figures 2). However, a weed-crop competition for 1.4 WAE and 2.8 WAE resulted in a yield loss of rice by 10 and 20%, respectively while a weed-free crop period of 6.3 WAE and 4.7 WAE documented a yield loss of rice by 10 and 20%, respectively during the second year (Figures 2). Johnson et al. (2004) reported that to attain a 95% weed-free paddy yield in the dry-DSR, these critical periods were predicted between 4 to 83 days after sowing (DAS). Our results revealed that weeds in DSR should be controlled at 11 days after crop emergence (DAE) and the crop should keep weed-free up to 44 DAE to obtain a 90% weed-free yield. Juraimi et al. (2009) also described that DSR should be kept weed-free from 0-72 DAS to get a 95% weed-free yield and the weed infestation during this period may result in a significant decline in the yield. Bajwa et al. (2020b) estimated the critical competition period of *P. hysterophorus* in direct-seeded rice between 4 and 8 WAE.

Table-5. Yield parameters of DSR rice as affected by different weed-crop competition periods

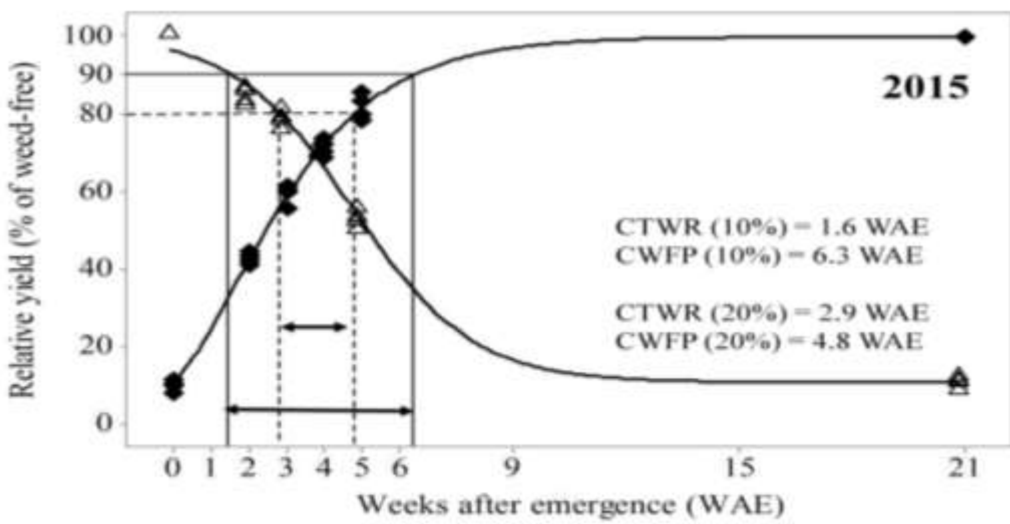
	No. of productive tillers (m^{-2})		No. of grains panicle^{-1}		1000-grain weight		Grain yield (t ha^{-1})	
Treatments	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**	**2015**	**2016**
Weed-crop competition periods (weeks)								
No weed competition (control)	439.5 a	479.5 a	108.8 a	117.3 a	22.37 a	22.71 a	3.88 a	4.08 a
2	408.3 b	422.3 b	94.55 b	96.93 b	21.00 c	21.66 b	3.26 b	3.45 b
3	371.8 c	381.0 c	85.40 c	88.07 c	20.12 d	20.62 c	3.04 c	3.08 c
4	263.2 d	278.3 d	75.65 d	77.45 de	18.95 e	19.50 d	2.71 d	2.76 d
5	209.2 e	216.3 e	65.72 e	67.40 f	18.20 f	18.75 e	2.03 f	2.14 f
Weed-free periods (weeks)								
5	358.7 c	366.2 c	90.50 bc	93.60 bc	21.62 b	22.32 a	3.17 bc	3.33 b
4	254.7 d	260.6 d	77.70 d	80.93 d	20.83 c	21.45 b	2.76 d	2.86 d
3	185.3 e	191.6 e	73.10 d	74.83 e	20.11 d	20.72 c	2.30 e	2.40 e
2	139.2 f	144.9 f	59.27 f	61.13 g	18.93 e	19.50 d	1.66 g	1.82 g
Full season weed competition (check)	91.75 g	96.75 g	50.20 g	54.15 h	17.57 g	18.10 f	0.38 h	0.40 h
Contrast comparison								
Competition for 2 WAE **Vs** (3 + 4) WAE	408 vs 317**	422 vs 329**	94.6 vs 80.5**	96.9 vs 82.8**	21.0 vs 19.5**	21.7 vs 20.1**	3268 vs 2876**	3450 vs 2923**
Competition for 3 WAE **Vs** (4 + 5) WAE	371 vs 236**	381 vs 247**	85.4 vs 70.7**	88.1 vs 72.4**	20.1 vs 18.6**	20.6 vs 19.1**	3040 vs 2373**	3084 vs 2453**
Weed-free for 5 WAE **Vs** (4 + 3) WAE	358 vs 226**	366 vs 226**	90.5 vs 77.9**	93.6 vs 77.9**	21.6 vs 21.1**	22.3 vs 21.1**	3179 vs 2634**	3334 vs 2634**
Weed-free for 4 WAE **Vs** (3 + 2) WAE	254 vs 168**	260 vs 168**	77.7 vs 68.0**	80.9 vs 68.0**	20.8 vs 20.1**	21.4 vs 20.1**	2767 vs 2112**	2867 vs 2112**
Weed-free for 3 WAE **Vs** (2 WAE + Full season weed competition)	185 vs 120**	191 vs 120**	73.1 vs 57.6**	74.8 vs 57.6**	20.1 vs 18.8**	20.7 vs 18.8**	2306 vs 1110**	2401 vs 1110**

Based on the least significant difference (LSD) test, the mean values in a column with different letters are substantially different ($P < 0.05$) from one another; ** indicates significant at $P < 0.01$

Table-6. Coefficients estimates to determine the effect of timing weed removal on relative paddy yield using a logistic model.

Year	**Coefficients**		
	K	**X**	**F**
2015	0.628 (0.040)	4.72(0.114)	1.11(0.019)
2016	0.609(0.049)	4.65(0.147)	1.11(0.024)

Data fit to equation, where X is the point of inflection (DAT), K and F are constants.



(b)

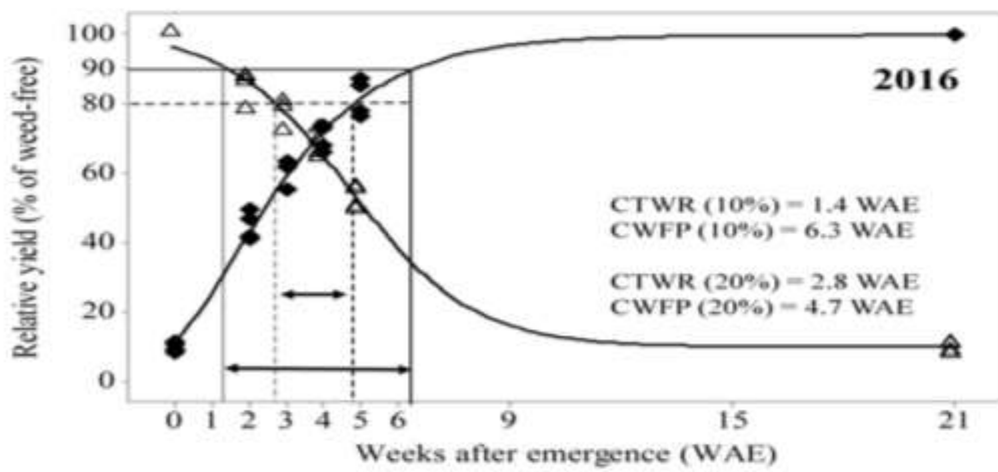


Figure-2. Critical period of weed competition in DSR in the year (a) 2015 and (b) 2016, CTWR = Critical timing of weed control, CWFP = Critical weed-free period

Conclusion

Weed-crop competition by mixed weed flora for the entire crop growing season caused a loss in the paddy yield of dry-DSR up to 90%, with depletion of 27.7, 5.4, 27.6 kg ha^{-1} of NPK, respectively. Weed competition by mixed weed flora for a period of 1.4 to 6.3 WAE caused a maximum reduction in the paddy yield of dry-DSR; hence the crop needs to be kept weed-free through this duration to avoid significant yield losses due to the weeds.

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Safdar ME: Supervised the experiment and approved final draft manuscript
Ehsan A: Performed experiment and manuscript write up
Maqbool R & Qamar R: Statistical analysis and manuscript write up
Ali A: Designed experimental layout and provided experimental inputs
Ali H: Helped in data collection and chemical analysis