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Critical period for alligator weed (*Alternanthera philoxeroides*) in puddled transplanted rice

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Abstract

Alligator weed (*Alternanthera philoxeroides*), an invasive plant in Pakistan due to its amphibious growth habit, has become a problematic weed for puddled transplanted rice (PTR). To assess the critical timing of removal (CTWR) and rice yield losses caused by this weed, a two-year field investigation was conducted. The treatments included varying alligator weed-crop competition durations for the initial 4 weeks following transplanting (WFT), 6 WFT, 8 WFT, and 10 WFT. The whole season, weedy and weed-free treatments were also kept. During both years, a gradual decline in paddy yield and rice quality parameters occurred with the prolongation in weedy period due to an increase in alligator weed's dry weight (up to 196%), N-uptake (up to 114%), P-uptake (up to124%), K-uptake (up to 134%), Cu-uptake (up to 101%), Fe-uptake (up to 21%), Zn-uptake (up to 81%), and Mn-uptake (up to 58%). Consequently, the full-season alligator weed competition resulted in the highest reductions in paddy yield (21.6%-22.3%), fertile tillers per hill (10.5%-11.5%), kernels per panicle (3.1%-3.7%), 1000-kernel weight (15.4%-21.2%), kernel amylose content (12.9%-13.5%), and protein content (12.5%-21.6%) during the first and second years' experiments, respectively. The alligator weed infestation increased in percentages of sterile spikelets (56%-69%), opaque kernels (27%-28%), and chalky kernels (17%-18%) of rice. The logistic model estimated the CTWR of the alligator weed in puddled transplanted rice (PTR) to be 6.1 WFT and 5.7 WFT in order to prevent 5% yield losses during the years 2011 and 2012.

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Introduction

Rice (*Oryza sativa* L.), an important cereal crop, is a major export commodity of Pakistan (Ashraf et al., 2006), which fulfills the food-energy requirement of almost half the global population (Chauhan and Johnson, 2011; Zafar and Jianlong, 2023). However, rice crop is heavily infested with weeds that cause severe yield losses (Shultana et al., 2013; Shekhawat et al., 2020). These losses from weed infestation may exceed the total losses from diseases and insect pests combined (Rahajaharilaza et al., 2025). It has been documented that weeds can decrease grain yield by 16–48% in transplanted rice (Mamun et al., 1993). Generally, weeds cause 15% to 20% of rice grain yield to be lost. This is dependent on the type and density of weeds present, when they germinate, and how long they compete, how competitive the crop is, and other crop management techniques used.

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According to an estimate, grain yield losses in extreme circumstances could exceed 50% (BRRI, 2006).

Alternanthera philoxeroides (Mart.) Griseb. that is called alligator weed is a member of the *Amaranthaceae* family. It is native to Argentina (Nahar et al., 2022) and an invasive weed in 32 different countries, including Pakistan (Tanveer et al., 2018). The adaptability to a wide range of environments, asexual propagation, and rapid waterborne dispersal make this weed a successful invasive plant (Mandal and Mondal, 2011; Puro et al., 2025). Alligator weed is a herbaceous, semi-prostrate, and emergent aquatic-terrestrial plant having a perennial growing habit (Julien, 1995; Puro et al., 2025). It has wider adaptability to upland and lowland conditions in regions of high, moderate, and low temperatures (Masoodi et al., 2013; Appelt et al., 2025). Its seed production is very rare; therefore, it reproduces through vegetative means such as root buds, apical or axillary stems (Clements et al., 2014; Zhu et al., 2015). Its dispersal to new areas occurs via stem fragmentation (Dugdale et al., 2010). Although alligator weed can grow both in terrestrial and aquatic environments, it proliferates well under semi-aquatic conditions by anchoring its roots vertically and horizontally into adjacent substrates in shallow waters or by establishing free-floating root mass (Clements et al., 2011; Li and Denich, 2024). Large hollow stems that offer buoyancy in aquatic environments and smaller solid stems in terrestrial environments cause the prostrate to grow larger (Julien et al., 1995). Worldwide, in addition to causing ecological disruption of water bodies, i.e., lakes, rivers, canals, and water channels, the alligator weed also has become problematic for rice, maize, soybean, some vegetables, and cotton (Ye et al., 2003; Puro et al., 2025). Due to the persistence of this weed, yields of rice, maize, and vegetables have been reported to reduce by 45%, 19%, and 20%, respectively (Yi, 1992; Zhang et al., 2004; Andres et al., 2013). Due to its semi-aquatic growing habit, this weed has become a major problem in puddled transplanted rice (Zhang et al., 2004; Mehmood et al., 2017).

To launch a successful management scheme against any weed, knowledge about its weed-crop competition period is necessary (Swanton and Weise, 1991; Hussen, 2021). The time duration in the life span of a crop during which weed prevalence results in the highest reduction in its yield is termed as critical period of weed-crop competition (CPWC) (Evans et al., 2003). The CPWC is an important attribute of crop-weed interaction, and its estimation is essential to decide when to control a weed (Evans et al., 2003; Adamic Zamljen and Leskovsek, 2024). Thus, the weed management program becomes cost-effective (Jones and Medd, 2000). Crop-to-crop variations occur regarding it due to a variety of factors, including weed species, weed density, emergence time, environmental conditions, and management techniques (Shehzad et al., 2011; Kumar et al., 2024). According to Mukherjee et al. (2008), the first 20–40 days of transplanted rice are CPWC because broadleaf weeds like *Ludwigia parviflora*, *Monochoria hastata,* and *Nymphoides indicum,* as well as grass weed *Echinochloa crus-galli*, reduced yield by 57–61 percent. However, in direct-seeded rice, Khaliq and Matloob (2011) found the initial 20 to 50 days after sowing to be the CPWC, as maximum rice grain yield reduction occurs during this period due to the presence of *E. colona*, *E. indica, Dactyloctenium aegyptium, Leptochloa chinensis, E. crus-galli,* C*yperus rotundus*, *C. iria*, *Ipomoea aquatica, Portulaca oleracea,* and *Trianthema portulacastrum.* As the alligator weed is a new weed in Pakistan that has heavily infested the rice crop, little information is available regarding its yield losses and CPWC in rice. Thus, the current scientific inquiry was designed to evaluate the rice grain yield losses and critical timing of weed removal in puddled transplanted rice.

Materials and Methods

Experimental location

A two-year experiment was conducted during two consecutive summer seasons of 2011 and 2012 in a field naturally infested with a dense stand of alligator weed at the research area of the University of Agriculture, Faisalabad, Pakistan. The study site is located at 31º N, latitude, 73º E, longitude, and 183.5 m above sea level. The soil of the study site was sandy clay-loam soil with a pH of 8.0 and an organic matter of 0.82%. The levels of available potassium, available phosphorus, and total nitrogen were 148 mg kg^{-1}, 6.24 mg kg^{-1}, and 0.66%, respectively. The cation exchange capacity was 4.1 cmol kg$^{-1,}$ and the bulk density was 1.54 g cm^{-3}. The meteorological data of both years is presented in **Figure 1**.

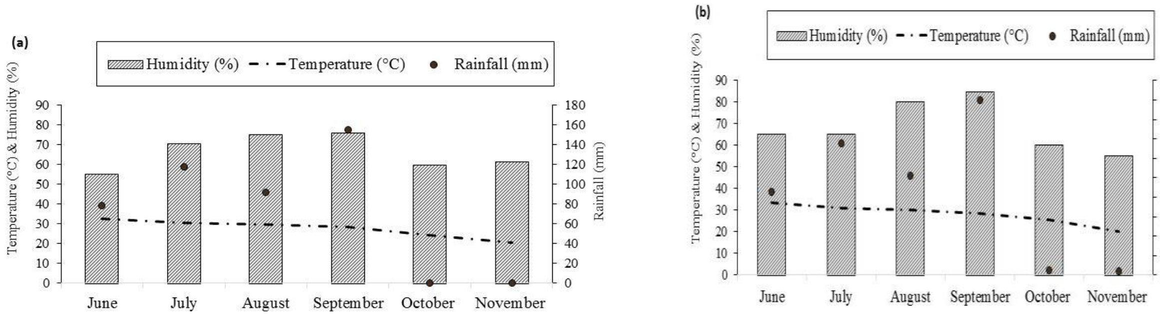

Figure 1: Meteorological data of the crop growing season in years (a) 2011 and (b) 2012

Experimental details

The rice variety "Basmati-515" was used as a test crop. Well-pulverized nursery beds were prepared and crop seed was sown over those on 14th and 15th of June, 2011 and 2012, respectively. In the initial 10 days of sowing, the nursery beds remained covered with paddy straw to protect germinating seed from desiccation and predation. A field heavily infested with alligator weed in the previous season was selected for study. The field was prepared by carrying out 2 cultivations followed by planking in standing water conditions. The 25-day-old seedlings were transplanted in the field. Manual transplanting was carried out by planting two seedlings hill^{-1} (hole), maintaining row-to-row and hill-to-hill distances of 25 cm. A plant population of 200,000 hills ha^{-1} was maintained.

At the time of final land preparation operation, nitrogen and phosphorus were applied at 150 kg ha^{-1} and 90 kg ha^{-1} as diammonium phosphate and urea, respectively. Nitrogen was applied in three splits, first at sowing, second at 25–30 days, and third at 45–50 days after transplanting. A total of 19 irrigations were applied to the crop during its entire growing season, with one irrigation occurring each week. Measures were taken to safeguard the rice crop from pests. To combat rice leaf folder, Karate 5-EC (Lambda-cyhalothrin) at 1000 mL ha^{-1} was used in mid-August. To combat rice blast, Green TM-1 70-WP (Thiophenate methyl) at 1 kg ha^{-1} was applied at the start of September. The experimental treatments were rice crop-alligator weed competition durations for periods of 4, 6, 8, and 10 weeks following rice transplanting (WFT). A full season of weedy and full season weed-free treatments were also kept for comparison. The layout pattern used was a randomized complete block design with four blocks. Net plot size was 6 m × 1 m.

Data collection

Alligator weed growth and competition: Data on alligator weed dry biomass were recorded twice after each competition period from two randomly selected quadrats, each measuring 1.0 m^{2,} from each experimental unit in respective plots of each block. The relative competitive index (RCI) of the alligator weed was computed by employing the Jolliffe et al. (1984) formula as follows:

$$RCI = \frac{Y_{Weed\ free} - Y_{Weed}}{Y_{Weed\ free}}\ X\ 100$$

Where $Y_{weed\ free}$ was the paddy yield of a full-season weed-free plot, and Y_{weed} was that of a full-season weedy plot.

Alligator weed's nutrient uptake: The alligator weed plants from each treatment were placed in an oven for drying at 70 °C till a constant weight was attained. The dried samples were ground using an electric grinder. Sulfuric acid (H_2SO_4) (10 mL) was added to 1 g dried powdered plant material in a conical flask and left overnight. After that, an aliquot of 5 mL of H_2O_2 was added to each flask, and the flasks were placed on a hot plate and heated all flasks slowly until the mixture became colorless. The digested material was diluted to 50 mL using distilled water and stored in clean plastic bottles for further processing. For N determination, an aliquot of 10 mL of diluted sample was drawn for the distillation of NH_3 in the presence of 40% NaOH by using a micro-Kjeldahl's apparatus. Nitrogen was gathered in the form of NH_3 in a receiver of a micro-Kjeldahl's apparatus, having 4% solution of boric acid, besides methyl red and bromocresol green indicators. The titration was carried out alongside 0.1N H_2SO_4. For determining phosphorus and potassium, a spectrophotometer (Beckman) and flame photometer (Jenway 8505) were used, respectively. The micronutrients (Cu, Fe, Zn, and Mn) were assessed using an atomic absorption spectrophotometer (Z-8200 Polarized Zeeman Atomic Absorption Spectrophotometer, Hitachi, Japan). Nitrogen, P, K, Cu, Fe, Zn, and Mn contents were multiplied by the alligator weed dry weight to get their respective uptakes.

Yield and yield-determining traits of rice: For plant height, 10 randomly selected tillers per plot were measured and then averaged. For panicle-bearing tillers per hill, 10 hills per plot, and for the number of kernels per panicle, 10 randomly selected panicles per plot were assessed and then averaged. The 1000-kernel weight was recorded in grams using an electric balance. Biological yield was measured by weighing the total above-ground crop biomass. However, paddy yield was recorded after harvesting and threshing, and adjusting the kernel weight to 14% moisture content. The kg per plot data of biological and paddy yields were converted to kilograms per hectare.

Rice quality traits: To obtain data on sterile spikelets, opaque kernels, and chalky kernels of rice, 10 panicles per plot were collected randomly. The spiketets were husked by a stake rice machine (Model THU-35 A). An electric lamp fixed to a flexible stand was used as a source of light to differentiate among sterile, opaque, and abortive kernels. The samples were then sorted out using a working board and a table lamp. Using a magnifying glass, normal kernels were distinguished from chalky kernels that had chalky areas in various rice sections. The porous filling and general chalky texture of the opaque kernels prevent light from passing through. Despite reaching their maximum size, they seem translucent because they lack carbs. The protein content of rice grains was ascertained by the micro-Kjeldahl method. The nitrogen concentration of the digest was measured by the titration or colorimetric ammonia test, and the protein was then converted by multiplying by a factor of 5.95. Grain amylose content was assessed by grinding kernels as per the method described by Juliano (1979). Using a spectrophotometer (Bausch & Lomb Spectronic-20), the blue color's intensity was measured at 620 nm.

Data analysis and model application

The experimental data obtained were subjected to statistical analysis following Fisher's analysis of variance technique (Steel et al., 1997) according to the randomized complete block design combined over years using the Statistix 8.1 computer software. The two-year data were pooled for parameters showing no significant difference between years. To quantify the impact of weedy duration on relative paddy yield, a three-parameter logistic model was employed. By the repetitious use of the NLIN method in SAS, in line with the Knezevic et al. (2002), the nonlinear regression model (equation) was fitted as follows:

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

Where Y is paddy yield (% of full season weed-free yield), T is the time in weeks following transplanting (WFT), while X represents the deflection point [weeks after transplanting (WAT)], and K and F are constants (Knezevic et al. 2002).

Results and Discussion

Alligator-weed competition

The results showed that varying alligator weed infestation durations significantly affected its dry biomass. The lowest dry weight (84.9-152.4 g m^{-2}) of the alligator weed was recorded with its 4-week infestation duration, and the maximum weed dry weight (227.2-452.1 g m^{-2}) was recorded in full-season weedy treatment, respectively, in both years of the study. Increased alligator weed dry weight in response to an extended weedy period may have been due to extended growth resulting in higher photosynthate accumulation and enhanced biomass. For example, increased weed biomass of rice was observed as the weed-crop competition duration increased (Zafar et al., 2010; Safdar et al., 2023). The phenomenon of increased dry biomass with an increase in weed competition duration was observed by Ali et al. (2015), who reported a steady increase in dry biomass of *Rhynchosia capitata* as its competition duration with the crop increased. *Rhynchosia capitata* produced maximum weed dry biomass where it competed with mungbean throughout the growing season. Safdar et al. (2016) found that the dry weight of *Parthenium hysterophorus* enhanced as the length of weed crop competition increased, and the maximum dry biomass was produced by full season competition treatment, whereas minimum dry biomass was recorded where competition duration in maize was 35 DAE. Tanveer et al. (2018) concluded from their study that the weed dry biomass of the alligator weed increased (up to 646%) with increasing its competition periods in maize. Different alligator weed infestation durations in rice significantly affected the relative competitive index (RCI) (**Table 1**). The RCI tended to increase linearly with increasing weed infestation periods. The highest value (21.69-22.28) was recorded in full season weedy treatment, whereas it was the minimum

(3.31-2.47) in 4-week infestation. Our results validate the findings of Cowan et al. (1998), who reported 32% to 99% soybean yield reduction with different density levels of barnyard grass (*Echinochloa crus-galli*) and pigweed (*Amaranthus retroflexus*). Likewise, a drastic yield reduction was reported due to weeds' infestation (Ijlal et al., 2011; Singh et al., 2022). Tanveer et al. (2018) found that the RCI inclined to rise linearly by decreasing the alligator weed-free and enhancing weed competition durations in maize crop.

Table 1: Dry weight and relative competition index (RCI) of alligator weed

Competition duration (WFT)	Dry Weight (g m^{-2})		Relative competitive index (RCI)	
	2011	2012	2011	2012
Zero week /Full season weed free/(Control)	-	-	-	-
4	84.9 d	152.4 d	3.31 e	2.47 e
6	166.8 c	158.6 d	5.00 d	4.77 d
8	180.9 b	230.1 c	8.14 c	6.69 c
10	224.5 a	254.1 b	15.9 b	15.2 b
Full season	227.2 a	452.1 a	21.6 a	22.2 a
LSD 5%	8.12	10.81	0.557	0.832
Year effect	177.0 b	249.4 a	10.82 a	10.29 b
LSD 5%	3.81		0.28	

Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

Alligator weed's nutrient uptake

The two-year pooled data of macronutrient (nitrogen, phosphorus, and potassium) and micronutrient (copper, iron, zinc, and manganese) uptakes (**Tables 2 and 3**) exhibit that all the macro- and micronutrients' uptakes by the alligator weed experienced a gradual increase in response to the prolongation in competition duration of this weed. Consequently, the full crop season alligator weed competition witnessed significantly the highest nitrogen (57.2 kg ha^{-1}), phosphorus (51.1 kg ha^{-1}), potassium (55.9 kg ha^{-1}), copper (21.1 g ha^{-1}), iron (138.9 g ha^{-1}), zinc (66.9 g ha^{-1}), and manganese (118.1 g ha^{-1}) uptakes by this weed. Increased nutrients' uptake by the alligator weed due to elongation in its competition duration seems to be the result of its increased biomass produced over the growing season. The existing findings are analogous to those of Ikram et al. (2012) and Anjum et al. (2007), who concluded that uncontrolled weedy conditions throughout the growing period of the cotton crop resulted in the maximum uptake of primary macronutrients by weeds. Similarly, Głowacka (2012) documented the highest uptake of copper, zinc, manganese, and iron by *Echinochloa crus-galli* under uncontrolled weedy conditions for the full growing season of maize.

Table 2: Macronutrients' uptake (kg ha^{-1}) by alligator weed

Competition duration (WFT)	Nitrogen uptake	Phosphorus uptake	Potassium uptake
Zero week /Full season weed free/(Control)	-	-	-
4	26.85 e	23.88 e	25.38 e
6	34.89 d	30.16 d	32.06 d
8	41.36 c	35.54 c	38.24 c
10	44.60 b	39.42 b	41.80 b
Full season weedy	57.21 a	51.17 a	55.97 a
LSD 5%	1.692	1.911	1.233

Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

Table 3: Micronutrients' uptake (g ha^{-1}) by alligator weed

Competition durations (WFT)	Copper	Iron uptake	Zinc uptake	Manganese
Zero week /Full season weed free/(Control)	-	-	-	-
4	10.89 e	118.61 c	38.27 e	77.27 d
6	13.80 d	126.65 b	44.78 d	92.35 c
8	16.25 c	136.34 a	48.21 c	99.60 b
10	17.33 b	130.22 b	52.61 b	100.40 b
Full season weedy	21.13 a	138.91 a	66.94 a	118.15 a
LSD 5%	0.589	4.663	1.951	3.126

Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

Yield and yield parameters of rice

The data for plant height, kernels per panicle, and fertile tillers hill^{-1} (**Table 4**) indicated that these parameters were significantly affected by different infestation durations of the alligator weed. Plant height was maximum (113.7-92.2 cm) in control and minimum (104.8-87.8 cm) in full season weedy treatment during the first and second years of the study. Reduction in plant height of rice with increasing weedy periods may have been due to reduced growth and development of rice resulting from more exploitation of nutrients by the alligator weed, and thus, more exhaustion of environmental reserves took place. Likewise, a significant decrease in plant height of rice was recorded when the plants were allowed to compete with *Fimbristylis miliacea* (Begum, 2006; Awan et al., 2020). Rice plant height significantly reduced when it competed with jungle rice (*Echinochloa colonum*) (Chauhan and Johnson, 2010). The highest number of fertile tillers per hill (18.9-17.2) was obtained under continuous weed-free conditions, whereas continuous weedy conditions produced the minimum fertile tillers per hill (16.9-15.2). Earlier, it has been recorded that prolonged weed crop competition causes poor vegetative growth during tillering, thereby reducing tiller count (Johnson et al., 1998). Sultana (2000) found that *Echinocloa crus-galli* (L.) Beauv reduced the number of rice (*Oryza sativa* L.) tillers up to 52%. Islam et al. (2003) found significantly maximum number of tillers in zero competition treatments. Weed crop infestation duration was reported to significantly affect the rice tillers in transplanted rice (Juraimi et al., 2009; Safdar et al., 2023).

Table 4: Rice yields and underlying traits of rice

Competition duration (WFT)	Plant height (cm)		Fertile tillers per hill		Kernels per panicle	
	2011	2012	2011	2012	2011	2012
Zero week /Full season weed free/(Control)	113.7 a	92.4 a	18.9 a	17.2 a	150.4 a	147.3 a
4	111.9 b	91.2 ab	18.4 b	16.7 b	149.5 ab	146.5 ab
6	108.2 b	90.4 abc	18.1 c	16.5 c	148.2 abc	145.7 b
8	106.0 bc	88.9 bc	17.7 d	16.1 d	147.2 bcd	144.4 c
10	105.9 bc	88.1 c	17.3 e	15.8 e	146.5 cd	143.3 cd
Full season weedy	104.8 c	87.8 c	16.9 f	15.2 f	144.8 d	142.7 d
LSD 5%	1.65	3.04	0.10	0.11	2.58	1.18
Year effect	108.4 a	89.8 b	17.9 a	16.2 b	147.8 a	145.0 b
LSD 5%	0.955		0.044		0.767	

Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

The maximum number of kernels per panicle (150.4-147.3) was recorded in fully weed-free conditions, whereas the minimum number of kernels per panicle (144.8-142.7) was found in full season competition duration treatments (**Table 4**). The lowest number in full-season weedy plots most likely could be related to more alligator weed dry weight, which depleted the nutrients. Our findings are per those of some earlier studies (Ekeleme et al., 2007; Begum et al., 2008; Abbas et al., 2021) in which reduced kernel count per panicle of rice due to prolonged weed competition was recorded. The data about 1000-kernel weight (**Table 5**) show that the maximum kernel weight (22.4-21.1 g) was obtained in the control treatments, whereas the minimum kernel weight (18.9-16.6 g) was obtained in full-season weedy treatments. Reduction in average kernel weight of rice with prolonged weed competition seems to have been due to weedy conditions prevailing during the grain-filling period that resulted in underdeveloped kernels. The rice crop completely consumed the growth resources without facing any alligator weed competition effects because of the removal of the alligator weed plants at early growth stages. The results are in agreement with the findings of Begum et al. (2008), who recorded reduced kernel weight when the weed species of *Fimbristylis milliaece* was allowed to compete with rice. Shultana et al. (2013) reported that rice dropped its average kernel weight in response to elongation in weedy conditions. Data in **Table 5** show that increasing the infestation duration of the alligator weed in rice gradually reduced its biological yield. The full season weed-free treatment (control) produced maximum biological yield (17714-16782 kg ha^{-1}) of rice, whereas the full season weedy treatment produced minimum biological yield (13643-12984 kg ha^{-1}). The rice crop attained better vegetative and reproductive growth under weed-free conditions, whereas prolonged weedy conditions suppressed growth and development of rice, resulting in reduced biological yield. Armin et al. (2007) stated that weed crop competition duration severely affected the biological yield of maize. For example, competition imposed by parthenium during the entire growing season of the maize crop resulted in decreased biological yield (Rehman et al., 2020). Data in **Table 5** showed that paddy yield was maximum (3914-3584 kg ha^{-1}) in full-season weed-free treatment and minimum (3065-2786 kg ha^{-1}) in full-season weedy plots. The decline in paddy yield of rice due to prolonged weedy conditions seems to be the result of a reduction in fertile tillers per hill, kernel count, and average kernel weight. Ekeleme et al. (2007) demonstrated that the transplanted rice dropped its yield with the increase of weed competition duration. In other studies, a substantial decline in rice yield was recorded with enhancing weed competition (Chauhan and Johnson, 2011; Shultana et al., 2013; Safdar et al., 2023).

Table 5: Yield and yield contributing parameters of rice

Competition duration (WFT)	1000-kernel weight (g)		Biological yield (kg ha^{-1})		Paddy yield (kg ha^{-1})	
	2011	2012	2011	2012	2011	2012
Zero week /Full season weed free/(Control)	22.4 a	21.1 a	17714 a	16782 a	3914 a	3584 a
4	21.5 ab	20.0 b	16906 b	16316 b	3785 b	3496 b
6	20.7 bc	18.6 c	16790 bc	15882 c	3718 b	3412 c
8	20.2 c	18.0 cd	16101 c	1559 c	3594 c	3344 c
10	19.8 cd	17.4 de	14695 d	13954 d	3288 d	3038 d
Full season weedy	18.9 d	16.6 e	13643 e	12984 e	3065 e	2786 e
LSD 5%	0.93	0.82	794.3	354.6	87.7	82.5
Year effect	20.6 a	18.6 b	15975 a	15247 b	3561 a	3277 b
LSD 5%	0.390		248.1		36.2	

Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

The logistic model of weed-crop competition periods is shown in **Figure 2**. The logistic model showed that the critical periods of the alligator weed removal (CTWR) for puddled transplanted rice were 6.1 weeks following transplanting (WFT) and 5.7 WFT in order to prevent 5% yield losses during the years 2011 and 2012, respectively. Different researchers estimated variable critical weed-crop competition periods of rice depending on growing conditions. A sigmoidal relationship between paddy yield and duration of weed competition in rice was earlier recorded (El-Desoki, 2003; Hussain et al., 2024). Johnson et al. (2004) estimated 38 DAS and 32 DAS to be the critical timings of weed removal in wet direct-seeded and dry direct-seeded rice, respectively.

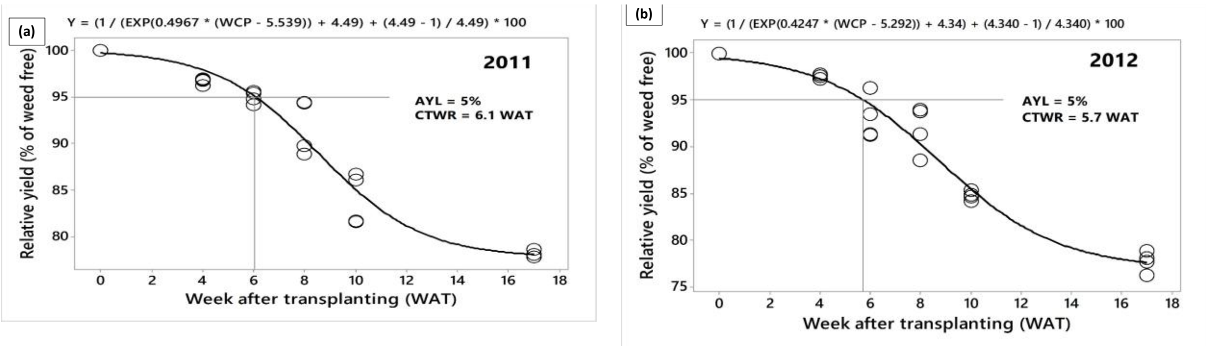

Figure 2: Logistic model showing relative grain yield of rice at different weed competition durations during the years (a) 2011 and (b) 2012

Rice quality traits

Data in **Table 6** show that during both years of the study, percentages of sterile spikelets, opaque kernels, and chalky kernels of rice significantly increased while normal kernels decreased with the extension in weed competition duration. Consequently, the highest sterile spikelets (4.65-5.31%), opaque kernels (10.1-10.9%), chalky kernels (14.2-14.8%), and the lowest normal kernels (66.3-68.5%) percentages were noted in the full-season weedy treatment. The weed competition stress during the reproductive growth phase of rice disturbed its pollination, fertilization and grain filling, resulting in rice quality traits. The highest percentage of sterile spikelets in full-season weedy plots compared to weedy for different durations has been reported (Maharjan et al.,2014; Arefin et al., 2018). In other studies maximum number of normal kernels in rice in the weed-free conditions was recorded (Safdar et al., 2023).

Table 6: Quality of rice kernels

Competition duration (WFT)	Sterile spikelets (%)		Opaque kernels (%)		Chalky kernels (%)		Normal kernels (%)	
	2011	2012	2011	2012	2011	2012	2011	2012
Zero week/Full season weed free/(Control)	2.98 d	3.14 d	7.95 e	8.55 c	12.1 f	12.6 c	74.7 a	73.4 a
4	3.22 c	3.25 d	8.62 d	8.74 c	12.4 e	12.8 c	73.3 b	72.8 a
6	3.54 c	3.80 c	9.12 c	8.95 c	12.8 d	13.1 bc	72.1 c	71.8 a
8	3.96 b	4.75 b	9.54 b	9.48 b	13.4 c	14.2 ab	70.6 d	68.7 b
10	4.15 b	4.88 ab	9.75 ab	0.52 ab	13.9 b	14.6 a	69.6 e	67.4 b
Full season weedy	4.65 a	5.31 a	10.1 a	10.9 a	14.2 a	14.8 a	68.5 f	66.3 b
LSD 5%	0.272	0.532	0.415	0.691	0.206	1.198	0.76	3.02
Year effect	3.77 b	4.19 a	9.18 b	9.59 a	13.1 b	13.7 a	71.5 a	70.1 b
LSD 5%	0.159		0.229		0.330		0.871	

Figures with dissimilar lettering differ significantly ($p \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

It is obvious from **Table 7** that maximum amylose (22.12-20.97%) and protein (7.98-7.45%) contents in rice grain were recorded from throughout weed-free plots, whereas throughout weedy treatment gave minimum values of amylose (19.25-18.12%), and protein (6.98-5.84%) contents. Rice plants growing in conditions free from the alligator weed infestation could have exploited the better growth resources during the rainy season, which might have improved the grain development and enhanced amylose contents. The alligator weed growing for a prolonged period of time along with the rice crop reduced the availability of nutrients, especially nitrogen for rice, thereby causing their scarcity during grain development and eventually reducing its grain protein contents. The results are reinforced by different studies (Akbar et al. 2011; Deng et al., 2022), who concluded that less weed competition conditions were helpful in improving the amylose and protein contents of rice grain.

Table 7: Amylose percentage and protein content of rice grain

Competition duration (WFT)	Amylose content (%)		Protein content (%)	
	2011	2012	2011	2012
Zero week /Full season weed free/(Control)	22.1 a	20.9 a	7.98 a	7.45 a
4	21.4 b	20.1 b	7.75 b	6.82 b
6	21.1 c	19.5 c	7.50 c	6.56 c
8	20.4 d	18.6 d	7.42 cd	6.24 d
10	20.1 e	18.2 e	7.25 d	6.11 d
Full season weedy	19.2 f	18.1 e	6.98 e	5.84 e
LSD 5%	0.180	0.283	0.197	0.248
Year effect	20.7 a	19.2 b	7.48 a	6.50 b
LSD 5%	0.098		0.084	

Figures with Figures with dissimilar lettering differ significantly ($P \leq 0.05$), LSD = Least significant difference test, WFT= Weeks following transplanting

Conclusion

The present findings conclude that the initial 5.7-6.1 weeks following transplanting is the critical timing of the alligator weed removal in transplanted rice, which means that it must be controlled during this period to prevent crop yield losses. Further, it is ascertained that this weed may cause up to 21.6-22.2% reduction in paddy yield.

Author(s), Editor(s) and Publisher's declarations

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Conceptualization and design of the study: AM, AT, RM, MES, MMJ. Conduction of experiment and collection of data: AM, RM. Analytical work: AM. Written first draft of the manuscript: AM, AT, RM, MES, MMJ, MAN. Helped to prepare figures and tables: AM, MES, MMJ. Statistical analysis of data: AM, MES, MMJ, MAN. Revision of the manuscript: AM, AT, MES, MMJ. Final draft reviewed and read by all authors.

Permissions and ethical compliance
This study does not involve human/animal subjects, and thus no ethical approval is required.

Handling of bio-hazardous materials
The authors certify that all experimental materials were handled with great care during collection and experimental procedures. After completion of the study, all materials were properly discarded to minimize/eliminate any types of bio-contamination(s).

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No supplementary material is included with this manuscript.

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The authors declare no conflict of interest.

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