

Impact assessment of nutrient accumulation, yield losses, and the critical period of competition of invasive Alligatorweed (*Alternanthera philoxeroides*) in sunflower

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Abstract: **Background:** Alligatorweed (*Alternanthera philoxeroides*) is an invasive weed species whose increasing infestations challenge sunflower production under climate change settings. **Objective:** Evaluate the impact of *A. philoxeroides* at different competition durations on nutrient accumulation and sunflower production, and determine the critical period of weed competition (CPWC). **Methods:** Two-year yield study was executed with treatments including *A. philoxeroides* competition durations i.e. weed free conditions for first 21, 28, 35, 42 and 49 days after crop emergence along with a full season weed free treatment and conversely weedy conditions for the first 21, 28, 35, 42 and 49 days after crop emergence along with a full season weedy treatment (90–100 days). **Results:** Weed infestation caused significant accumulation of nutrients, weedy for full season caused more accumulation of macronutrients (N, P and K at 62, 48,

55 kg ha⁻¹, respectively) and micronutrients (Cu, Fe, Mn and Zn at 19, 186, 137, 72 g ha⁻¹, respectively). Full season weedy produced more weed biomass (2098 kg ha⁻¹) and caused maximum reduction in achene (55%) and oil yield (50%) of sunflower. Four parameters log-logistic model revealed that *A. philoxeroides* infestation for 56.66 DACE and 64.49 DACE caused 50% achene yield loss in sunflower in 2020 and 2021, respectively. Further, model predicted *A. philoxeroides* competition for 4 DACE to 40.97 DACE and 6.36 DACE to 45.29 DACE as CPWC to cause 5% and 10% achene yield losses, respectively. **Conclusions:** Timely control of *A. philoxeroides* within the CPWC is crucial for mitigating yield losses and ensuring sustainable sunflower production. Furthermore, the nutrient accumulation potential of aquatic *A. philoxeroides* could potentially be harnessed for heavy metal accumulation, benefiting both aquatic and terrestrial ecosystems.

Keywords: Aquatic weed; Achene yield; Cu accumulation; Sunflower oil; Nutrient uptake; Invasive weeds; Four parameters log-logistic model

Journal Information:

ISSN - 2675-9462

Website: <http://awsjournal.org>

Journal of the Brazilian Weed Science Society

How to cite: Ahmad T, Abbas T, Alawadi HFN, Tanveer A, Abdullah F, Nadeem MA, Zafar M, Wahid A, Farooq N. Impact assessment of nutrient accumulation, yield losses, and the critical period of competition of invasive Alligatorweed (*Alternanthera philoxeroides*) in sunflower. *Adv Weed Sci.* 2025;43:e020250088

<https://doi.org/10.51694/AdvWeedSci/2025;43:00020>

Approved by:

Editor in Chief: Anderson Nunes Gabardo

Associate Editor: Andre da Rosa Ulguim

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Received: September 25, 2024

Approved: May 20, 2025

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1. Introduction

Sunflower is ranked fourth most important oil seed crop and cultivated on 25.56 million hectares worldwide with an annual achene production 55.54 million metric tons (US Department of Agriculture, 2024). Increasing population pressure has increased the demand of sunflower seed, oil and byproducts, there is need to optimize sunflower production to fulfill increasing food demand. Sunflower oil is known for its excellent nutritional and medicinal value, its byproducts are used as human diet and livestock food (Adeleke, Babalola, 2020). In addition to its use as edible oil, both sunflower oil and sunflower biodiesel are promising sources of alternate fuel to mitigate air pollution associated with diesel usage (Khan et al., 2023). Changes in climate conditions especially rise in temperature and changes in perceptions are affecting sunflower production by influencing nutrient availability, soil moisture, insect and disease attack, weed infestation and input availability (Awais et al., 2018; Adeleke, Babalola, 2020; Debaeke et al., 2021). Sunflower has moderate drought tolerance; however, severe drought can negatively affect its growth and yield (Hussain et al., 2018). As a result, sunflower may face significant challenges under drought stress in the context of climate change (Debaeke et al., 2021).

Competing for resources such as light, nutrients, space, and water, weeds vary in their level of competitiveness, influenced by factors such as the duration of competition, the weed species in competition (Abbas et al., 2014), and the overall density of weeds in the crop (Stefanic et al., 2023). Sunflower is very sensitive to weed competition especially at early seed seedling stage and mechanical weeding may harm young delicate sunflower plants. Biological and economic performance of sunflower is severely affected by weed competition and weed control (especially at critical period of competition) is necessary to achieve economical production (Pannacci, Tei, 2014; Stefanic et al., 2023).

Invasive weeds are becoming an ecological problem and are a greatest threat to biodiversity and ecosystem components throughout the world (Sun et al., 2020; Abbas et al., 2025). Among the invasive weeds, *Alternanthera philoxeroides* (Mart.) Griseb is a fast spreading competitive allelopathic invasive weed (Mehmood et al., 2018). Its indigenous place is South America but is now colonizing in all parts

of the world. Global climate change increases the interspecific competitiveness of *A. philoxeroides* making it dominant over native weed species leading to its more invasion under climate change (Wu et al., 2017; Abbas et al., 2025). It exhibits strong tolerance to soil heavy metal pollution and water stress compared to native weed species (Ren et al., 2023; Lin et al., 2024). It is considered troublesome invasive weed of rice, maize, soybean and fruit orchards (causing 19–45% yield losses) in more than 30 countries globally (Tanveer et al., 2018). Its adaptability to grow in both aquatic and terrestrial environments, high heat tolerance, strong allelopathic potential, and perennial growth nature make it a potential weed that can disrupt any cropping system in a changing climate (Abbas et al., 2014; Wu et al., 2017; Tanveer et al., 2018; Lin et al., 2024).

To best of our knowledge no study has been conducted to check *A. philoxeroides* competition with sunflower crop. The increasing invasion of *A. philoxeroides* necessitates an understanding of its competition dynamics with sunflower for effective control. We hypothesize that the length and timing of *A. philoxeroides* competition differentially affect sunflower growth and yield, and that identifying the critical period of weed competition (CPWC) will help mitigate yield losses. This two-year field study was conducted to evaluate the impact of varying coexistence periods between crops and weeds on sunflower growth and yield. Additionally, the critical competition period of *A. philoxeroides* that resulted in 5% and 10% achene yield losses was also predicted.

2. Materials and Methods

Sunflower variety Hysun-33 was sown on 8 August, 2020 and 23 August, 2021 on 75 cm in a field with a known history of *A. philoxeroides* infestation, using 75.0 cm row spacing and a 22.5 cm plant-to-plant distance. The experimental plots measured 9.2 m × 6.0 m. Seed rate was 5 kg ha⁻¹. NPK was applied @ 150, 100 and 62 kg ha⁻¹. Urea was used as nitrogen (N) source, DAP (di-ammonium phosphate) for phosphorus (P) while sulphate of potash (SOP) was used to fulfill the requirements of potash (K). The full dose of P and K was applied by spreading it uniformly at the time of sowing while only one fifth of N was applied at sowing. Remaining amount of N was applied with 1st irrigation (half bag of urea at 15 days after crop emergence – DACE), 2nd irrigation (half bag of urea at 30 DACE) and at flowering (one bag of urea). Five irrigations each with an interval of 15 days were applied. Every irrigation was of 3 acre inches. Twelve different treatments were studied, including: T₁: weed-free throughout the growth period (control/weed free check), T₂: weed-free for 21 DACE, T₃: weed-free for 28 DACE, T₄: weed-free for 35 DACE, T₅: weed-free for 42 DACE, T₆: weed-free for 49 DACE, T₇: weedy for 100 DACE (weedy check), T₈: weedy for 21 DACE, T₉: weedy for 28

DACE, T₁₀: weedy for 35 DACE, T₁₁: weedy for 42 DACE, T₁₂: weedy for 49 DACE. *A. philoxeroides* plants were not allowed to compete with sunflower for specified days after emergence of sunflower in treatments 2-6 whereas in treatments 7-12, *A. philoxeroides* was allowed to compete with the sunflower crop for specified days after emergence of crop. In weed free check, *A. philoxeroides* plants were constantly uprooted and no competition was allowed whereas in weedy check, no *A. philoxeroides* seedling was removed throughout the growing season of sunflower. Weedy and weed-free conditions were maintained to collect data under extreme scenarios. Including weedy and weed-free conditions as treatments, rather than as factors, is standard methodology in experiments evaluating the critical period of weed control (Ritz et al., 2015; Stefanic et al., 2023). Randomized complete block design (RCBD) was used to layout the field experiment. All other weeds except *A. philoxeroides* was uprooted manually soon after emergence. Other crop management operations were kept uniform except those under study.

At the end of respective competition period of *A. philoxeroides*, weed plants were manually removed from each plot, and weed density and biomass were determined. Standard procedures were followed to record data on different parameters of *A. philoxeroides* i.e. dry weight, NPK-uptake (Bremner, 1965; Wolf, 1982), micro-nutrients uptake (Jones et al., 1991) and sunflower plant population, head diameter, number of achenes per head, achene weight per head, 1,000-achene weight, achene yield, achene oil contents.

Fisher's analysis of variance technique was used to analyze the data statistically and Tukey's honestly significant difference (HSD) was used to compare different treatment means at 5% p value (Steel et al., 1997) using Statistix 8.1 statistical computer package (Statistix 2006). If a parameter showed non-significant variations over the year of study, then mean values for both the years were presented and discussed.

A four-parameter log-logistic model was used to determine the CPWC, as this model provides robust estimates of the nonlinear relationship between weed competition duration and yield loss (Knezevic et al., 2007). Model parameters were estimated using non-linear regression in Statistix 8.1. Yield losses were calculated by four parameters log-logistic model whose equation is as under (Knezevic et al., 2007):

$$Y = \frac{[C + (D - C)]}{[1 + \exp \{B (\log X - \log E)\}]}$$

Y represents the achene yield of sunflower, X is the duration (Day after crop emergence DACE), C is the lower limit, D is the upper limit while E is the DACE giving a 50% yield of the maximum and the minimum yield, and B is the slope of the line (rate of change) at E.

3. Results and Discussion

3.1 *A. philoxeroides* density and dry weight

Weedy and weed free durations significantly affected the population of *A. philoxeroides* but the year affect was non-significant; hence, data regarding *A. philoxeroides* population was discussed on an average basis and is presented in Table 1. *A. philoxeroides* population increased with increase in weedy durations while on the contrary, *A. philoxeroides* population decreased with increased weed free durations. When plots were kept weedy throughout the growing season of sunflower, maximum population of *A. philoxeroides* (209.33 plants m⁻²) was reported. This was followed by the weedy period for 49 days after emergence, in which 159.45 plants m⁻² of *A. philoxeroides* was recorded. Minimum weed population (18.28 plants m⁻²) was observed by that of weed free duration of 49 DACE followed by that of weed free period for 42 DACE and 35 DACE, respectively.

Increase in population of *A. philoxeroides* with reduced weed free durations and increased competition durations was due to the least disturbance in weed growth, more time to germinate and more availability of resources for rapid regeneration. Due to initially slow growing habit of sunflower, it provided congenial environment for abundant weed growth and crop canopy did not cover the ground. The *A. philoxeroides* was suppressed during later stages, mainly due to smothering of late emerged weeds by crop canopy (Mehmood et al., 2018; Tanveer et al., 2018).

Dry weight of *A. philoxeroides* (Table 1) reveal that weed free and weedy durations has a significant impact on dry weight of *A. philoxeroides*. As weed free durations in sunflower were increased, gradual reductions in the dry weight of *A. philoxeroides* was recorded. Significantly more *A. philoxeroides* dry weights (209.80 g m⁻² and 187.25 g m⁻² during 2020 and 2021, respectively) and minimum *A. philoxeroides* dry weights (11.23 g m⁻² and 7.89 g m⁻²) were recorded with the plots in which full season competition of *A. philoxeroides* with sunflower and weed free durations of 49 DACE were granted, respectively. Plots in which weedy conditions were maintained for 21 DACE produced *A. philoxeroides* dry weight statistically at par to the plots in which weed free conditions were maintained for 28 DACE.

Increased dry weight of *A. philoxeroides* as a result of reduced weed free duration and enhanced competition durations may be a consequence of added advantage to *A. philoxeroides* to steal important nutrients from the soil depriving the crop from those resources (Stefanic et al., 2023; Torun et al., 2021). These resources are than used exclusively for photosynthesis, rapid growth and development of *A. philoxeroides* plants (Mehmood et al., 2018; Tanveer et al., 2018).

3.2 Macronutrient (N, P and K) uptake by *A. philoxeroides* and sunflower

Nitrogen (N), Phosphorus (P) and Potash (K) uptake of *A. philoxeroides* as influenced by different weed free and weedy duration are displayed in Table 1. Data regarding N

Table 1 - Effect of critical period of weed crop competition on density, dry weight and nutrient uptake by alligator weed

Treatment	weed density (m ⁻²)	dry weight (g m ⁻²)		N uptake (kg ha ⁻¹)		P uptake (kg ha ⁻¹)		K uptake (kg ha ⁻¹)	
	Average of two years	2020	2021	2020	2021	2020	2021	2020	2021
T ₁		---	---	---	---	---	---	---	---
T ₂		34.9 cdef	24.18 cde	8.68 cde	5.82 cde	6.40 cde	4.28 cde	7.86 cdef	5.32 cde
T ₃	81.31 ef	29.38 def	20.46 de	7.30 cde	4.92 cde	5.31 cde	3.57 cde	6.14 def	4.18 de
T ₄	40.64 g	18.88 ef	13.19 e	4.47 e	3.03 de	3.42 e	2.31 de	3.71 ef	2.54 e
T ₅	31.74 gh	11.09 f	11.23 f	2.59 e	1.76 e	1.98 e	1.34 e	2.01 f	1.38 e
T ₆	27.67 gh	7.77 e	7.89 e	2.53 e	1.733 e	1.94 e	1.32 e	1.96 f	1.35 e
T ₇	18.28 h	209.8 a	187.25 a	61.87 a	53.24 a	47.63 a	40.87 a	55.26 a	48.12 a
T ₈	209.33 a	27.36 def	19.01 de	6.70 de	4.51 de	4.93 de	3.31 cde	5.89 def	4.00 de
T ₉	69.1 f	58.44 bcde	52.91 bcd	14.83 bcde	12.98 bcd	10.81 bcde	9.44 bcd	13.92 bcde	12.31 bcd
T ₁₀	94.29 de	66.68 bcd	60.15 bc	17.34 bcd	15.12 bc	12.59 bcd	10.94 bc	15.93 bcd	14.03 bc
T ₁₁	103.71 d	73.61 bc	66.16 b	19.47 bc	16.90 b	14.34 bc	12.42 b	18.12 bc	15.90 b
T ₁₂	126.62 c	93.16 b	83.43 b	26.09 b	22.54 b	18.37 b	15.82 b	23.07 b	20.16 b
HSD	159.45 b	40.828	36.193	12.364	10.59	9.0451	7.7408	11.04	9.58
Year	87.47	57.684 A	49.308 B	15.624 A	12.960 B	11.610 A	9.601 B	13.99 A	11.75 B
HSD	14.99	6.1586		1.8655		1.3713		1.67	

T₁= Control/ Weed free check, T₂=Weed free for 21 days after crop emergence (DACE), T₃= Weed free for 28 DACE, T₄=Weed free for 35 DACE, T₅=Weed free for 42 DACE, T₆=Weed free for 49 DACE, T₇=Weedy for full season (90-100 days), T₈=Weedy for 21 DACE, T₉=Weedy for 28 DACE, T₁₀=Weedy for 35 DACE, T₁₁=Weedy for 42 DACE, T₁₂=Weedy for 49 DACE. In a column, means sharing different letters statistically vary from one another on the basis of Tukey's HSD test (p < 0.05).

uptake reveals that, in general as the weed free durations are shortened and weedy conditions are elongated the uptake of N by *A. philoxeroides* increases. In 2020, the weed-free treatment for 49 DACE resulted in the highest N uptake (32.56 g kg⁻¹), followed by the full-season weedy treatment with 29.49 g kg⁻¹. While in 2021, the highest N uptake (28.43 g kg⁻¹) was recorded in the full-season weedy treatment, followed by the weedy treatment for 49 DACE. Significantly less uptake of N by *A. philoxeroides* (23.35 g kg⁻¹ and 15.67 g kg⁻¹ in 2020 and 2021, respectively) was recorded in plots in which weed free conditions were maintained for 42 DACE.

As far as the impact of weedy and weed free durations on P uptake by *A. philoxeroides* is concerned (Table 1), the weed-free treatment for 49 DACE resulted in the highest P uptake (24.97 g kg⁻¹), followed by the full-season weedy treatment with 22.70 g kg⁻¹ in 2020. While in 2021, the highest P uptake (21.83 g kg⁻¹) was recorded in the full-season weedy treatment, followed by the weedy treatment for 49 DACE. Contrastingly, the minimum alligator weed P- uptake (17.85 and 11.93 g kg⁻¹ in years 2020 and 2021, respectively) were noted from weed free for 42 DACE.

The K uptake increases gradually with increased weedy durations. Maximum K uptake by *A. philoxeroides* (26.34 g kg⁻¹ and 25.70 g kg⁻¹ in 2020 and 2021, respectively) were observed in the treatments in which there was full season competition of *A. philoxeroides* with sunflower (weedy check). Significantly minimum K uptake (18.12 g kg⁻¹ and 12.29 g kg⁻¹ in 2020 and 2021, respectively) was attained by the weed free for 42 DACE.

The uptake of nitrogen (N), phosphorus (P), and potassium (K) by sunflower under varying weed-free and weedy durations is presented in Table 2. The data reveal that as weed-free periods were shortened and weedy conditions were prolonged, nutrient uptake by sunflower decreased significantly. When weeds were allowed to compete throughout the entire growing season, sunflower exhibited the lowest nutrient uptake, with values of 16.20–16.96 g kg⁻¹ for N, 3.16–3.30 g kg⁻¹ for P, and 24.07–25.20 g kg⁻¹ for K during the 2020 and 2021 growing seasons. In contrast, under full-season weed-free conditions, sunflower achieved maximum nutrient uptake, reaching 26.67–28.26 g kg⁻¹ for N, 6.40–6.71 g kg⁻¹ for P, and 35.76–37.67 g kg⁻¹ for K in the same period. Prolonged weed competition consistently reduced NPK uptake, with full-season *A. philoxeroides* infestation causing reductions of up to 39% for N, 52% for P, and 33% for K compared to weed-free conditions.

Increased NPK uptake of *A. philoxeroides* as a result of reduced weed free duration and enhanced competition durations may be a consequence of increased growth period of *A. philoxeroides* allowing it to capture as much nutrients as it can from the soil depriving the crop from those resources. Previously uncontrolled *A. philoxeroides* for full season in maize crop caused up to 18, 13 and 16 kg ha⁻¹ uptake of N, P and K, respectively (Tanveer et al., 2018). Higher N, P and K uptake by *A. philoxeroides* in sunflower crop might

be due to strong competitive potential of this weed with sunflower. Studies have shown that *A. philoxeroides* has competitive advantages over native species (Sun et al., 2022). The strong competitive ability of *A. philoxeroides* is attributed to multiple factors, including its allelopathic properties (Abbas et al., 2014), rapid biomass accumulation, and tolerance to environmental stresses such as high temperatures and heavy metal pollution (Wu et al., 2017; Lin et al., 2024). These adaptive traits allow it to efficiently monopolize resources, limiting crop development.

3.3 Micronutrient (Cu, Fe, Mn and Zn) uptake by *A. philoxeroides* and sunflower

Uptake of micronutrients (Cu, Fe, Mn and Zn) by *A. philoxeroides* was significantly increased with increase in weedy durations while decreased with increased weed free durations (Table 2). Maximum uptake of Cu (9.16–7.82 mg ka⁻¹), Fe, (85.64–88.47 mg ka⁻¹), Mn (65.46–57.56 mg ka⁻¹) and Zn (34.34–30.20 mg ka⁻¹) was observed in plots with weedy for full season for both year 2020 and 2021. With exception of maximum Cu uptake (9.52 mg ka⁻¹) from weed free for 42 DACE in 2020. Lowest uptake of Cu, Fe, Mn and Zn was noted with plots kept weed free for 49 DACE.

The uptake of Cu, Fe, Mn and Zn by sunflower under varying weed-free and weedy durations is presented in Table 4. The data reveal that as weed-free periods were shortened and weedy conditions were prolonged, Cu, Fe, Mn and Zn uptake by sunflower decreased significantly. When weeds were allowed to compete for the entire growing season, sunflower exhibited the lowest nutrient uptake, with values of 2.53–3.01 mg ka⁻¹ for Cu, 15.66–17.52 mg ka⁻¹ for Fe, 5.49–6.52 mg ka⁻¹ for Mn, and 1.88–2.96 mg ka⁻¹ for Zn during the 2020 and 2021 growing seasons. In contrast, under full-season weed-free conditions, sunflower achieved maximum nutrient uptake, reaching 7.23–8.31 mg ka⁻¹ for Cu, 36.86–33.31 mg ka⁻¹ for Fe, 10.29–11.12 mg ka⁻¹ for Mn, and 4.52–5.46 mg ka⁻¹ for Zn in the same period. Prolonged weed competition consistently reduced micronutrient uptake by sunflower, with full-season *A. philoxeroides* infestation causing reductions of up to 64% for Cu, 58% for Fe, 41% for Mn, and 58% for Zn compared to weed-free conditions.

The linear increase in Cu, Fe, Mn, and Zn uptake by *A. philoxeroides* and sunflower with reduced weed free durations and increased weed competition with sunflower crop is a consequence of excessive uptake of micronutrients by the *A. philoxeroides* in the initial growth period of sunflower as sunflower is more prone to early weed infestation. Maximum uptake of micronutrients in plots with more periods of weed infestation is the result of more biomass produced by *A. philoxeroides*. Consequently, due to strong competition for micronutrients between weed and crop plants the minimum micronutrients uptake by sunflower was exhibited in these plots. High uptake of Cd, Pb and Zn from wastewater by *A. philoxeroides* has been

Table 2 - Effect of critical period of weed crop competition on micro nutrient uptake by alligator weed

Treatment	Cu uptake (g ha ⁻¹)		Fe uptake (g ha ⁻¹)		Mn uptake (g ha ⁻¹)		Zn uptake (g ha ⁻¹)	
	2020	2021	2020	2021	2020	2021	2020	2021
T ₁	---	---	---	---	---	---	---	---
T ₂	2.52 de	1.67 d	1.67 d	16.70 def	17.39 def	11.89 def	9.32 cd	6.37 cde
T ₃	2.01 de	1.34 d	1.34 d	11.93 ef	12.46 ef	8.57 ef	7.12 cd	4.9 de
T ₄	1.28 e	0.86 d	0.86 d	6.96 ef	6.97 f	4.81 f	4.30 d	2.97 de
T ₅	0.74 e	0.50 d	0.50 d	3.69 f	3.91 f	2.7 f	2.26 d	1.56 e
T ₆	0.74 e	0.50 d	0.50 d	3.33 f	3.94 f	2.74 f	2.06 d	1.44 e
T ₇	19.22 a	16.41 a	16.14 a	185.62 a	137.34 a	120.76 a	72.04 a	63.35 a
T ₈	1.91 e	1.28 d	1.28 d	11.91 ef	12.62 ef	8.66 ef	6.79 cd	4.66 de
T ₉	4.43 cd	3.84 c	3.84 c	39.48 cde	31.28 cde	27.94 cde	16.52 bcd	14.75 bcde
T ₁₀	5.48 c	4.73 c	4.73 c	47.94 bcd	36.09 cd	32.11 cd	18.66 bcd	16.60 bcd
T ₁₁	6.34 bc	5.46 bc	5.46 bc	57.73 bc	43.71 bc	38.74 bc	22.45 bc	19.90 bc
T ₁₂	8.64 b	7.40 b	7.40 b	77.95 b	59.81 b	52.79 b	30.23 b	26.68 b
HSD	2.45	2.08	2.08	32.65	23.34	20.49	16.69	14.66
Year	4.85 A	4.00 B	4.00 B	42.11 B	33.23 A	28.34 B	17.43 A	14.84 B
HSD	0.39		5.74		3.57		2.51	

T₁= Control/ Weed free check, T₂=Weed free for 21 days after crop emergence (DACE), T₃= Weed free for 28 DACE, T₄=Weed free for 35 DACE, T₅=Weed free for 42 DACE, T₆=Weed free for 49 DACE, T₇=Weedy for full season (90-100 days), T₈=Weedy for 21 DACE, T₉=Weedy for 28 DACE, T₁₀=Weedy for 35 DACE, T₁₁=Weedy for 42 DACE, T₁₂=Weedy for 49 DACE. In a column, Means sharing different letters statistically vary from one another on the basis of Tukey's HSD test (p < 0.05).

reported by Liu et al. (2007). The ability of *Alternanthera philoxeroides* to produce antioxidant enzymes and maintain higher endogenous peroxidase concentrations in response to increasing heavy metal concentrations, may serve as a mechanism empowering its growth in such environments and assisting metal accumulation (Beals et al., 2023). In competition with rice crop grown under standing water condition, *A. philoxeroides* caused high uptake of micronutrients including Cu, Fe, Zn and Mn (Mehmood et al., 2018). Current strong nutrient uptake under non-aquatic conditions by this aquatic weed (*A. philoxeroides*) might be due to its adaptability, competitive nature and long infestation duration with sunflower crop (Sun et al., 2022; Abbas et al., 2025).

3.4 Effect of *A. philoxeroides* competition on yield components of sunflower

The yield components of sunflower (head diameter, number of achenes per head, achene weight per head and 1,000-achene weight) were significantly influenced by various weedy and weed free durations of *A. philoxeroides* (Table 3). Results illustrates that maximum head diameter (18.44 cm and 20.03 cm), number of achenes per head (1,026 and 1,067), achene weight per head (52 g and 54 g) and 1,000-achene weight (50 g and 50 g) of sunflower was observed in the plots where *A. philoxeroides* was not allowed to compete with sunflower (control/weed free check) and it was statistically higher than all other treatments in 2020 and 2021, respectively. It was followed by that of weed free

for 49 DACE. Yield components decreases gradually with the gradual decrease in the weed free period ultimately reaching to a point where *A. philoxeroides* compete with sunflower for full growing season (weedy check) resulting in minimum yield component of sunflower.

Reduction in yield components of sunflower due to *A. philoxeroides* infestation may be attributed to the heavy competition pressure imposed by the *A. philoxeroides*. As results exhibited increased biomass production and nutrient uptake by weed which leads to less nutrient availability for sunflower crop. Torun et al. (2021) revealed that increasing weed infestation in sunflower enhances weed biomass and negatively affects yield-contributing traits, ultimately reducing final yield. Moreover, the potent allelopathic impact exhibited by *A. philoxeroides*, as investigated in prior studies against various crop species, could potentially inhibit the growth and yield components of sunflower (Abbas et al., 2014, Tanveer et al., 2018a, b). Recent studies have shown that the antioxidant defense systems of crops are unable to mitigate the phytotoxic effects of phenolics produced by allelopathic weeds (Matloob et al., 2025).

3.5 Sunflower Yield and Critical Period of *A. philoxeroides* Competition

Achene and oil yield of sunflower was significantly influenced by different weed free and weedy durations of *A. philoxeroides* (Table 4). Achene and oil yield of sunflower increased with decreased weedy durations and

with increased weed free durations. Plots kept weed free through the growing season produced significantly higher achene yield (3,200.6 and 3,297 kg ha⁻¹ in 2020 and 2021, respectively). Weed free check was statistically followed by achene yield recorded from the plots in which no *A. philoxeroides* was allowed to germinate for 49 DACE for both the years. Lowest sunflower achene yield (1,446.1 kg ha⁻¹ in 2020 and 1,496.4 kg ha⁻¹ in 2021) was recorded from the plots where *A. philoxeroides* was left unchecked throughout the growing season of sunflower. This was followed by those of weed free for 21 DACE, weedy for 42 DACE, 35 DACE, 28 DACE and 21 DACE which were statistically at par to one another for both years. Whole season *A. philoxeroides* infestation caused 55% and 48% achene yield losses in 2020 and 2021, respectively. Weed free sunflower plots achieved statistically maximum values for sunflower oil yield (1,371 and 1,412 kg ha⁻¹ in 2020 and 2021, respectively) which was followed by plots in which *A. philoxeroides* was not allowed to grow for 49 DACE. However, minimum sunflower oil yield (586.1 and 606.5 kg ha⁻¹ in 2020 and 2021, respectively) was recorded in the plots in which *A. philoxeroides* kept uncontrolled for full growing season of sunflower and it was followed by the oil yield recorded from the plots where weedy duration of 49, 42, 35, 28 and 21 DACE were applied. Full season *A. philoxeroides* infestation caused up to 50% reduction in sunflower oil yield. Steady decrease in oil yield of sunflower with increased weedy durations

Table 4 - Effect of critical period of weed crop competition on achene and oil yield of sunflower

Treatment	Achene yield (kg ha ⁻¹)		Oil yield (kg ha ⁻¹)	
	2020	2021	2020	2021
T ₁	3201 a	3297 a	1371.1 a	1412.4 a
T ₂	1715 e	1672 ef	708 e	689.9 ef
T ₃	2025 d	1982 d	841.5 d	823.7 d
T ₄	2106 d	2287 c	869.6 d	944.6 c
T ₅	2392 c	2526 bc	965.2 b	1019.2 c
T ₆	2673 b	2770 b	1099 b	1139.1 b
T ₇	1446 f	1496 f	586.1 f	606.5 f
T ₈	1800 e	1866 de	735.7 e	762.6 de
T ₉	1778 e	1841 de	738.4 e	760.1 de
T ₁₀	1749 e	1805 de	714.7 e	737.6 de
T ₁₁	1740 e	1771 de	727.4 e	740.6 de
T ₁₂	1446 e	1723 ef	685.3 e	708.8 ef
HSD	207.12	250.49	85.00	102.70
Year	2025 B	2086 A	836 B	862 A
HSD	37.94		15.57	

T1= Control/ Weed free check, T2=Weed free for 21 days after crop emergence (DACE), T3= Weed free for 28 DACE, T4=Weed free for 35 DACE, T5=Weed free for 42 DACE, T6=Weed free for 49 DACE, T7=Weedy for full season (90-100 days), T8=Weedy for 21 DACE, T9=Weedy for 28 DACE, T10=Weedy for 35 DACE, T11=Weedy for 42 DACE, T12=Weedy for 49 DACE. In a column, Means sharing different letters statistically vary from one another on the basis of Tukey's HSD test (p < 0.05).

Table 3 - Effect of critical period of weed crop competition on yield components of sunflower.

Treatment	Head diameter(cm)		Number of achenes per head		Achene weight per head (g)		1000-achene weight (g)	
	2020	2021	2020	2021	2020	2021	2020	2021
T ₁	18.45 a	20.04 a	1026 a	1067 a	52.109 a	54.143 a	49.828 a	50.213 a
T ₂	14.49 cdef	15.78 cdef	824 cdef	856 cdef	33.344 cd	34.637 cd	39.656 de	40.043 de
T ₃	14.86 bcde	16.16 bcde	838 cde	871 cde	33.967 bc	35.282 bc	40.039 d	40.413 d
T ₄	15.15 bcd	16.48 bcd	848 bcd	881 bcd	34.324 bc	35.657 bc	40.83 cd	41.194 cd
T ₅	15.55 bc	16.90 bc	877 bc	911 bc	38.045 b	39.528 b	41.94 bc	42.297 bc
T ₆	15.69 b	17.05 b	899 b	934 b	38.33 b	39.818 b	42.912 b	43.26 b
T ₇	12.53 g	13.68 g	711 h	738 h	24.304 f	25.255 f	33.775 h	34.187 g
T ₈	14.72 bcde	16.02 bcde	825 cdef	857 cdef	33.60 cd	34.86 cd	39.053 d	39.449 d
T ₉	14.13 def	15.39 def	804 defg	836 defg	30.772 cde	31.974 cde	38.07 ef	38.472 ef
T ₁₀	13.97 ef	15.22 def	791 efg	822 efg	30.131 cde	31.309 cde	37.641 fg	38.053 f
T ₁₁	13.80 ef	15.04 ef	782 fg	812 fg	29.41 de	30.55 de	37.184 fg	37.607 f
T ₁₂	13.45 fg	14.67 fg	763 gh	792 gh	27.998 ef	29.087 ef	36.258 g	36.685 f
HSD	1.16	1.26	53	55	4.36	4.53	1.79	1.80
Year	14.73 B	16.04 A	832 B	864 A	33.86 B	35.18 A	39.84 B	40.24 A
HSD	0.18		8.0853		0.66		0.267	

T1= Control/ Weed free check, T2=Weed free for 21 days after crop emergence (DACE), T3= Weed free for 28 DACE, T4=Weed free for 35 DACE, T5=Weed free for 42 DACE, T6=Weed free for 49 DACE, T7=Weedy for full season (90-100 days), T8=Weedy for 21 DACE, T9=Weedy for 28 DACE, T10=Weedy for 35 DACE, T11=Weedy for 42 DACE, T12=Weedy for 49 DACE. In a column, Means sharing different letters statistically vary from one another on the basis of Tukey's HSD test (p < 0.05).

and reduced weed free period may be attributed to the low achene yield of sunflower.

The results of four parameters log-logistic model are presented in Table 7 and 8, and fitted curves for the model are given in Figures 1 and 2. The results regarding weedy periods (Table 5) revealed that 56.66 DACE and 64.49 DACE were the competition periods causing a 50% achene yield loss in sunflower in 2015 and 2016, which suggests that *A. philoxeroides* management should be executed well before this time to avoid 50% yield loss. The anticipated decrease rate in sunflower achene yield at this time was 4.59 kg ha⁻¹ and 2.72 kg ha⁻¹ in 2015 and 2016, respectively. The results regarding weed free durations (Table 6), showed that maintaining the weed free conditions for 43.24 DACE and 37.14 DACE resulted 50% more sunflower achene yield in 2020 and 2021 than weedy check, which suggests that *A. philoxeroides* management should be at least executed up to this time to get 50% yield. The anticipated increase rate in sunflower achene yield at this time was 3.38 kg ha⁻¹ and 2.76 kg ha⁻¹ in 2020 and 2021, respectively.

In 5% AYL (acceptable yield losses), the duration of CPWC of *A. philoxeroides* began at 4.12 DACE and 4.72 DACE and continued until the 39.53 DACE and 42.41 DACE in 2020 and 2021, respectively (Table 7). In 10%, AYL the duration of CPWC of *A. philoxeroides* began at 6.11 DACE and 6.62 DACE and continued until the 44.20 DACE and 46.19 DACE in 2015 and 2016, respectively.

The strong competition of *A. philoxeroides* exhibited in weed biomass production, high nutrient uptake and reduction of yield components contributed toward achene and oil yield reduction of sunflower (Torun et al., 2021). Further, model results determined that weed-free for 45 days after crop emergence and 4 days of unchecked growth of *A. philoxeroides* are the critical stages for *A. philoxeroides* competition in sunflower crop. *A. philoxeroides* infestation at density of 32 plants m⁻² caused 42% reduction in transplanted rice yield (Mehmood et al., 2018). Further, full season weedy period of *A. philoxeroides* in maize crop caused up to 45% reduction in maize grain yield (Tanveer et al., 2018a). Comparatively higher yield losses in sunflower than other crops may be due to its crop specific allelopathic

influence (Abbas et al., 2017), adaptability of the sunflower crop ecosystem, and dominant competition for resources.

The growth stage of the sunflower at which *A. philoxeroides* competition can result in severe reduction of final yield is considered as critical period of crop-weed competition. Further increase in weedy duration than 4 DACE or decrease in weed free period from 45 DACE can result in severe reductions in achene yield of sunflower. Recently, Stefanic et al. (2023) estimated CPWC of weed community (consisting of total 32 weed species) starting from 14 DACE and continued till 98 DACE to cause 5% yield losses in sunflower. The CPWC of weed community (dominated by four weed species) was found 25 DACE to 43 DACE in sunflower crop (Wanjari et al., 2000). The short competition period of *A. philoxeroides* as determined in this study showed its strong interference with sunflower crop. Therefore, for economically efficient production of sunflower, *A. philoxeroides* must be controlled at critical competition period.

The present study revealed strong interference of *A. philoxeroides* with sunflower crop, evident through substantial weed biomass production, high macro- and micronutrient depletion, considerable losses in achene and oil yield, and short duration of CPWC. As *A. philoxeroides* is rapidly spreading invasive weed, its growth and spread are favored by the effects of global warming (Wu et al., 2017; Abbas et al., 2025). Control of this weed has emerged as a global challenge for crop production, affecting aquatic and terrestrial ecosystems. In the present study we first

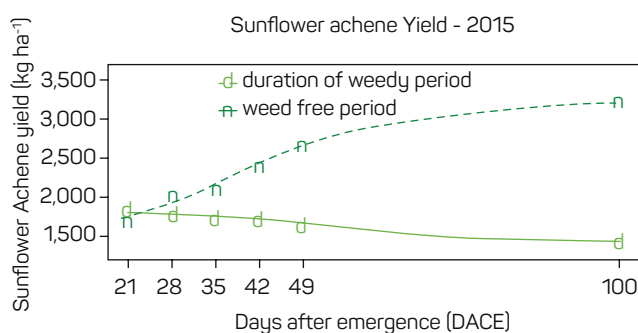


Figure 2 - Sunflower Achene yield as predicted by 4 parameter log logistic model in 2020.

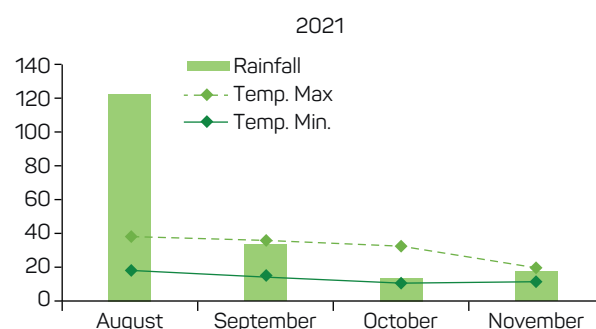
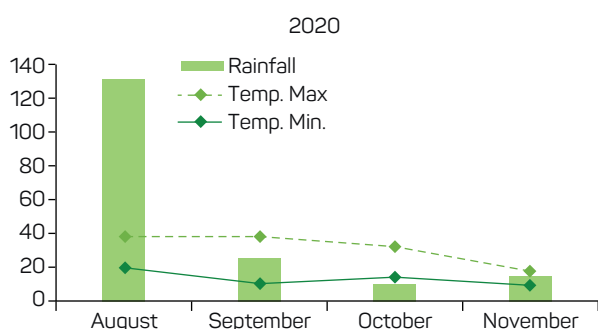


Figure 1 - Monthly mean rainfall, maximum and minimum temperatures during the sunflower growing season in 2020 and 2021 at site of experiments.

Table 5 - Model fit (four parameters Log-logistic model) characterizing the association between sunflower achene yield and weedy periods of *A. philoxeroides* in sunflower.

Factor	Year	Weedy periods (parameter estimates)				Model Fit
		C	D	B	E	
Achene yield	2020	1419.70 (69.44)	1801.42 (27.78)	4.59 (3.04)	56.66 (8.85)	Four parameter-Log-logistic
Achene yield	2021	1378.37 (69.74)	1888.44 (14.80)	2.74 (0.57)	64.49 (7.21)	Four parameter-Log-logistic

In the table, C represents minimum limit/lower asymptote, D represents maximum limit / upper asymptote, E represents the time in days after crop emergence which gave 50% of upper asymptote (D) while B represents the rate of change/ slope of the line at 50% of upper asymptote. Note: values in brackets represent standard errors.

Table 6. Model Fit (four parameters Log-logistic model) characterizing the association between sunflower achene yield and weed free periods of *A. philoxeroides* in sunflower.

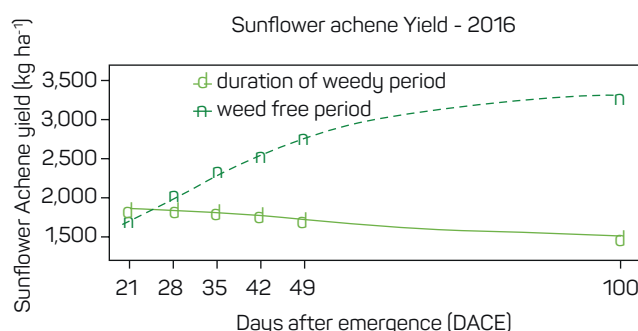
Factor	Year	Weed free period (parameter estimates)				Model Fit
		C	D	B	E	
Achene yield	2020	1617.86 (64.40)	3299.57 (44.12)	3.38 (0.41)	43.24 (0.87)	Four parameter-Log-logistic
Achene yield	2021	1311.53 (28.28)	3427.45 (12.09)	2.76 (0.08)	37.14 (0.32)	Four parameter-Log-logistic

In the table, C represents minimum limit/lower asymptote, D represents maximum limit / upper asymptote, E represents the time in days after crop emergence which gave 50% of upper asymptote (D) while B represents the rate of change/ slope of the line at 50% of upper asymptote. Note: values in brackets represent Standard errors.

Table 7. Estimation of critical period of *A. philoxeroides* competition with sunflower through Log-logistic model at 5% and 10% AYL along with standard errors in brackets.

Factor	AYL	Beginning of CPWC (DACE)	End of CPWC (DACE)
Achene yield 2020	5%	4.12 (1.15)	39.53 (2.78)
Achene yield 2021	5%	4.72 (1.19)	42.41 (3.03)
Achene yield 2020	10%	6.11 (1.50)	44.20 (2.75)
Achene yield 2021	10%	6.62 (1.72)	46.19 (3.25)

AYL represents acceptable yield loss at 5 and 10%. CPWC = critical period of weed competition.

**Figure 3. Sunflower Achene yield as predicted by 4 parameter log logistic model in 2021**

time, estimated CPWC of *A. philoxeroides* in sunflower. The identification of CPWC (4–45 DACE) suggests that early season weed control is crucial. As sunflower facing new

challenges and growing climate change threats, prioritizing integrated weed management, such as pre-emergence herbicides, mechanical control, and cultural practices is essential to reduce yield losses and sustain production (Debaeke et al., 2021; Hussain et al., 2022; Santos et al., 2023). In the current study, competition data was recorded starting from 21 DACE. However, future studies can be conducted to investigate potential competitive effects during earlier developmental phases, prior to 21 DACE.

4. Conclusion

Alternanthera philoxeroides severely reduces sunflower yield, with full-season competition causing 55% achene and 50% oil yield losses. The identification of CPWC (4–45 DACE) suggests that early season weed control is crucial for sustainable production. Additionally, *A. philoxeroides*' nutrient accumulation potential could be leveraged for phytoremediation in polluted ecosystems.

Authors' contributions

All authors conceived and designed the research. TA, AT, and TA: conceptualization. AT, TA, and NF: methodology. NF, MY, and MZ: analysis and investigation. TA, MAN, and NF: interpretation of data. TA: writing - original draft preparation TA and NF: writing - review and editing.

Funding

No funding received for this research.

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