



RESEARCH ARTICLE

Dynamics of weed flora and integrated weed management for enhancing sunflower (*Helianthus annuus* L.) productivity

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Abstract

At the instructional farm of Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, a field experiment was carried out in the rabi season of 2022–23 to investigate the impact of integrated weed management techniques on productivity of sunflower (*Helianthus annuus* L.). The experiment was laid out in a factorial randomised block design (FRBD) with the conventional spacing of 60 cm × 30 cm and seven weed management treatments: T₁: pendimethalin 1 kg a. i. ha⁻¹ as pre-emergence followed by one power weeding at 35 days after sowing (DAS); T₂: one power weeding at 35 DAS; T₃: pendimethalin 1 kg a. i. ha⁻¹ as pre-emergence followed by quizalofop-p-ethyl 37.5 g a.i. ha⁻¹ at 20 DAS; T₄: farmers practice (two inter cultivations at 20 and 40 DAS followed by one hand weeding at 30 DAS); T₅: one intercultivation at 20 DAS followed by one hand weeding at 30 DAS; T₆: weed-free condition (three hand weedings at 15, 30 and 45 DAS); and T₇: unweeded control, replicated thrice. Sunflower hybrid DRS-1 was used as the test crop. Eighteen weed species were predominant in the experimental site, with broadleaf weeds accounting for the majority (55.6 %), followed by grasses (33.3 %) and sedges (11.1 %). At every stage of growth, the weed-free treatment had the best weed control efficiency (WCE), whereas farmers practices had the lowest weed index (WI). The maximum head diameter (17.0 cm), filled seeds per head (1243) and lowest sterility (6.12 %) were observed in weed-free plots, which were comparable to farmers practices. The unweeded control had the lowest yields, whereas weed-free circumstances produced the highest seed yield (2048 kg ha⁻¹), harvest index (32.05 %) and oil production (819 kg ha⁻¹), which were equivalent to farmers practices and specific integrated weed management treatments.

Keywords: herbicides; integrated weed management; weed dynamics; weed flora

Introduction

The sunflower (*Helianthus annuus* L.) is an important oilseed crop that is indigenous to North America and a member of the asteraceae family. Sunflower stands out prominent among the edible oilseed crops due to its excellent oil quality, bland flavour and increased oil yield per unit area. Its importance among oilseed crops is further increased by its photo-insensitivity, capacity to thrive in a variety of agro-climatic conditions, short growing duration and broad range of adaptability, which makes it appropriate for a variety of cropping systems. Weed problem in sunflower is considered serious problem because they compete for water, nutrients, light and space that reduce crop growth and yield (1). One of the most significant pressures throughout the crop season is weed competition. There are a number of reasons why sunflower yields are poor, but weeds pose the biggest danger, causing a 45–55 % reduction in seed output (2). The sunflower crop develops slowly at first, enabling weeds to proliferate and compete with the crop for nutrients, moisture, light and space. This results in poorer yields and decreased agricultural

input efficacy (3, 4). The major causes of heavy weed infestation in sunflowers include increased fertiliser usage, frequent watering, slower crop development in the early stages and wider spacing. Weeding by hand is challenging since it requires a lot of work and time. For sunflower weed control, herbicides are a practical and successful solution (5).

According to research findings, weeds in sunflower fields may extract up to 48.2 kg of nitrogen (N) and 14.4 kg of phosphorus (P) per hectare, resulting in yield losses to the tune of 18.6–36.3 % (6–8). Chemical herbicides have historically been a major part of sunflower weed management; however, this strategy carries the danger of environmental pollution and the incidence of herbicide resistance. Integrated weed management (IWM) provides a long-term, sustainable solution to the problem by judiciously combining preventive, cultural, mechanical, physical, biological and chemical methods with techniques like crop rotation, tillage, herbicide rotation and mixtures, optimised nutrition and irrigation. By combining these tactics, IWM ensures efficient weed control,

enhancing long-term sunflower productivity while reducing threats to the economy, soil and human health which ensures environment safety. By examining the interactions between sunflower and weed species, this research seeks to evaluate the effectiveness of weed management practices in sunflower for reducing weed competition, improving weed control efficiency (WCE) and enhancing crop growth, yield and overall productivity.

Materials and Methods

In order to assess the impacts of weed control techniques on sunflower, a field study was conducted in the rabi season of 2023 at the instructional farm of Odisha University of Agriculture and Technology (OUAT), Bhubaneswar. The sandy loam soil used in the experiment had a medium organic carbon content (0.59 %), a pH of 5.9 and a somewhat acidic response. Potassium (K) (262.3 kg ha⁻¹) and N (297 kg ha⁻¹) were both medium in the soil, whereas P (2.60 kg ha⁻¹) was low. The total rainfall received during the cropping season was 113.10 mm. The mean maximum and minimum atmospheric temperature during the cropping season were 33.3 °C and 20.2 °C, respectively. The experiment was laid out in a factorial randomised block design (FRBD) with 3 replications. Plot size was 30 m². The treatments consisted of spacing levels 60 cm × 30 cm. The treatments included T₁: pendimethalin at 1 kg a. i. ha⁻¹ as a pre-emergence spray followed by one weeding with a power weeder at 35 days after sowing (DAS); T₂: one weeding by power weeder at 35 DAS; T₃: pendimethalin at 1 kg a. i. ha⁻¹ as pre-emergence followed by quizalofop-ethyl 10 % EC at 37.5 g a. i. ha⁻¹ as a post-emergence spray at 20 DAS; T₄: farmers practice involving two inter cultivations at 20 and 40 DAS followed by one hand weeding at 30 DAS; T₅: one intercultivation at 20 DAS followed by one hand weeding at 30 DAS; T₆: weed-free condition maintained through three hand weedings at 15, 30 and 45 DAS; and T₇: unweeded control. As the test crop, the sunflower hybrid DRS-1 was fertilised evenly with the suggested dosage of 60: 80: 60 kg ha⁻¹ of N: P₂O₅: K₂O. Every agronomic technique was maintained consistently during treatments, with the exception of weed control and spacing. Before analysis, the square root transformation ($\sqrt{x + 0.5}$) was applied to the weed density and dry weight data. The square root transformation ($\sqrt{x + 0.5}$) was applied to the data to stabilise the variance and normalise the distribution, particularly where the observations involved count data or exhibited heterogeneity of variance. Such data often deviate from

the assumptions of normality and homoscedasticity required for valid analysis of variance (ANOVA). The addition of the constant 0.5 before transformation helps to adjust for zero or very small values, ensuring that all observations are suitably transformed. This transformation reduces skewness, improves the approximation to normal distribution and enhances the reliability and validity of statistical inferences. Standard error of means (SEm. $\pm$) and critical differences were computed at a 5 % significance level to represent various treatment effects. The Excel OP Stat and OP Stat software was used in the data analysis. Plant height, head diameter, seed output and 100-seed weight were all noted at harvest. To calculate the weed index (WI), the formula proposed from a previous study is used (9).

Results

Weed flora associated with sunflower

The weed flora associated with the sunflower crop during the rabi season of 2022–23 comprised a diverse mixture of grasses, sedges and broad-leaved species (Table 1). The degree of weed infestation directly affects the intensity of competitive relation between sunflower crop and weeds (10). A rich and diverse weed spectrum under the current agro-climatic circumstances was shown by the 18 weed species that were identified from the experimental field. With a proportion of 55.6 % of the overall weed population, broad-leaved weeds were the most prevalent and problematic to the crop. Grassy weeds came in 2nd position with 33.3 % population, while sedges made up the least amounting to 11.1 %. Aggressive grassy and sedge species that are well suited to summer conditions made up the majority of the narrow-leaved weed flora. *Cyperus rotundus* and *Cyperus iria* were the most common sedges, whereas *Cynodon dactylon*, *Dactyloctenium aegyptium*, *Eleusine indica*, *Digitaria ciliaris*, *Digitaria sanguinalis* and *Ischaemum rugosum* were the most identified grassy weeds. Majority of the weed flora were broad-leaved, such as *Heliotropium indicum*, *Ageratum conyzoides*, *Alternanthera philoxeroides*, *Phyllanthus niruri*, *Spilanthes acmella*, *Cirsium arvense* and *Amaranthus viridis*. These broad-leaved species dominance under summer sunflower farming demonstrated their flexibility and fierce competitiveness. In general, the diverse weed flora highlighted the necessity of integration of varied weed management techniques to successfully control broad-leaved weeds, grasses and sedges in sunflower fields.

Table 1. Major weed floral composition of the experimental plot

Sl.no.	Botanical name	Family	Common name	Ontogeny	Group
1	<i>Eleusine indica</i>	Poaceae	Indian goose grass	Perennial	Grass
2	<i>Cynodon dactylon</i>	Poaceae	Bermuda grass	Perennial	Grass
3	<i>Dactyloctenium aegyptium</i>	Poaceae	Crowfoot grass	Annual	Grass
4	<i>Digitaria ciliaris</i>	Poaceae	Crabgrass	Annual	Grass
5	<i>Digitaria sanguinalis</i>	Poaceae	Hairy crabgrass	Annual	Grass
6	<i>Ischaemum rugosum</i>	Poaceae	Saramolla grass	Perennial	Grass
7	<i>Cyperus rotundus</i>	Cyperaceae	Nutgrass	Perennial	Sedge
8	<i>Cyperus iria</i>	Cyperaceae	Rice flat sedge	Annual	Sedge
9	<i>Heliotropium indicum</i>	Boraginaceae	Indian heliotrope	Annual	Broad leaf
10	<i>Alternanthera philoxeroides</i>	Amaranthaceae	Alligator weed	Perennial	Broadleaf
11	<i>Amaranthus viridis</i>	Amaranthaceae	Slender amaranth	Annual	Broad leaf
12	<i>Spilanthes acmella</i>	Asteraceae	Paracress	Perennial	Broadleaf
13	<i>Ageratum conyzoides</i>	Asteraceae	Billygoat weed	Annual	Broad leaf
14	<i>Phyllanthus niruri</i>	Phyllanthaceae	Stone breaker	Perennial	Broad leaf
15	<i>Cirsium arvense</i>	Asteraceae	Canada thistle	Perennial	Broad leaf
16	<i>Physalis minima</i>	Solanaceae	Ground cherry	Annual	Broad leaf
17	<i>Cleome rutidosperma</i>	Cleomaceae	Fringed spider flower	Annual	Broad leaf
18	<i>Croton sparsiflorus</i>	Euphorbiaceae	Ban tulsi	Perennial	Broad leaf

Weed density

Over the course of the growing phase, the population of grass fluctuated considerably. The weed-free treatment with three hand weedings performed at 15, 30 and 45 DAS exhibited the lowest grass density (2.63 m⁻²) at 30 DAS. Similar patterns were seen at 60 DAS and harvest, when weed-free treatment reported the lowest grass population (3.57 and 4.63 m⁻²), followed by farmers practices (4.32 and 5.51 m⁻²). At 30 DAS, 60 DAS and at harvest, unweeded control continuously reported the maximum grass population and was comparable to one power weeder operation conducted at 35 DAS. At every stage, the sedge population was likewise greatly impacted by weed management practices. Weed-free treatment had the lowest sedge population (3.56 m⁻²) at 30 DAS, followed by farmers practice (4.68 m⁻²). Weed-free treatment maintained the lowest sedge density at 60 DAS and harvest (4.37 and 5.25 m⁻², respectively), followed by farmers practice (5.35 and 5.72 m⁻²). The weed-free plots recorded the lowest population at 30 DAS (3.28 m⁻²), 60 DAS (3.84 m⁻²) and at harvest (5.27 m⁻²). At every point of observation, there were substantial differences in the total weed population among different treatments. At 30 DAS (5.42 m⁻²), 60 DAS (6.75 m⁻²) and harvest (8.70 m⁻²), weed-free treatment had the lowest overall weed density, followed by farmers practices (7.45, 8.77 and 10.04 m⁻², respectively) recorded at 30, 60 DAS and at harvest. The comparable performance of unweeded control with a single power weeder operation at 35 DAS suggests that one-time mechanical weeding is insufficient to manage continuous weed emergence, especially under favourable conditions. Similar trends were observed in sedge and broad-leaved weed populations, where weed-free treatment maintained the lowest densities, followed by farmers practices, while unweeded control recorded the maximum populations. The progressive increase in weed density across all treatments over time reflects the continuous emergence and establishment of weeds, emphasising the importance of sustained weed control measures throughout the crop growth period.

Dry weight of weeds

At different phases of crop growth, the total dry weights of weeds under various weed control techniques were shown to have considerable effect. The weed-free treatment recorded the lowest weed dry weight (2.12 g m⁻²) at 30 DAS, but it was comparable to farmers practice (3.25 g m⁻²) which included two inter cultivation at 20 and 40 DAS followed by one hand weeding at 30 DAS. The weed-free treatment had the lowest weed dry weight (3.29 g m⁻²) at 60 DAS, followed by the farmers practice treatment (4.26 g m⁻²) (Tables 2 and 3). The weed-free treatment had the lowest weed dry weight (4.33 g m⁻²) at harvest, which was comparable to the farmers practice (4.92 g m⁻²) treatment. The unweeded control showed the highest weed dry weight at 30 DAS and harvest, but it was statistically comparable to the treatment with single weeding operation performed with power weeder at 35 DAS. The farmers practice, which involved two inter-cultivations at 20 and 40 DAS followed by one hand weeding at 30 DAS, also proved effective in reducing weed biomass, as reflected by its comparable performance with the weed-free treatment at all stages. In contrast, the unweeded control plots recorded the highest weed dry weight throughout the crop growth period, indicating unchecked weed proliferation and biomass accumulation due to the absence of control measures.

Table 2. Effect of integrated weed management methods on total weed population (no. m⁻²) at different growth stages of sunflower

Treatments	Grasses			Sedges			Broadleaf weed			Total weed		
	30	60	Harvest	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₁ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by 1 PW at 35 DAS	6.14 (37.20)	5.74 (32.44)	7.31 (52.90)	7.09 (49.79)	8.07 (64.66)	8.87 (78.12)	7.26 (52.17)	9.19 (84.00)	9.72 (94.05)	11.82 (139.16)	13.48 (181.10)	15.02 (225.07)
T ₂ : one PW at 35 DAS	8.06 (64.44)	7.07 (49.52)	8.76 (76.23)	9.06 (81.62)	9.75 (94.60)	10.89 (118.19)	9.91 (97.64)	10.29 (105.35)	10.78 (115.75)	15.63 (243.70)	15.81 (249.46)	17.63 (310.17)
T ₃ : pendimethalin as pre-emergence followed by Quizalofop-p-ethyl at 37.5 g a. i./ha at 20 DAS	4.65 (21.13)	5.24 (27.04)	6.70 (44.46)	5.83 (33.49)	6.70 (44.37)	7.41 (54.47)	6.30 (39.22)	6.87 (46.65)	7.52 (56.10)	9.71 (93.84)	10.89 (118.05)	12.47 (155.03)
T ₄ : farmers practice (2 IC at 20 & 40 DAS followed by 1 HW at 30 DAS)	3.43 (11.25)	4.32 (18.20)	5.51 (29.91)	4.68 (21.45)	5.35 (28.12)	5.72 (32.24)	4.77 (22.32)	5.54 (30.15)	6.22 (38.24)	7.45 (55.02)	8.77 (76.47)	10.04 (100.39)
T ₅ : one IC at 20 DAS followed by 1 HW at 30 DAS	3.75 (13.60)	4.78 (22.34)	6.12 (36.94)	5.00 (24.49)	6.00 (35.48)	6.62 (43.39)	4.99 (24.42)	5.99 (35.35)	6.77 (45.35)	7.93 (62.51)	9.68 (93.16)	11.23 (125.68)
T ₆ : weed free (3 HW at 15, 30 and 45 DAS)	2.63 (6.45)	3.57 (12.32)	4.63 (20.92)	3.56 (12.22)	4.37 (18.57)	5.25 (27.09)	3.28 (10.30)	3.84 (14.30)	5.27 (27.28)	5.42 (28.97)	6.75 (45.19)	8.70 (75.28)
T ₇ : unweeded control	8.33 (68.91)	8.82 (77.35)	9.34 (86.65)	9.48 (89.31)	10.80 (116.16)	11.61 (134.34)	10.25 (104.59)	10.98 (120.15)	11.68 (135.90)	16.23 (262.80)	17.72 (313.66)	18.90 (356.89)
SEm (±)	0.177	0.193	0.227	0.212	0.242	0.266	0.224	0.231	0.271	0.353	0.393	0.441
CD (p = 0.05)	0.51	0.56	0.66	0.62	0.70	0.77	0.65	0.67	0.79	1.03	1.14	1.28

Note: DAS: days after sowing; HW: hand weeding; IC: inter-cultivation; PW: power weeder.

Table 3. Effect of integrated weed management methods on dry weight at different growth stages

Treatment	30 DAS	60 DAS	At harvest
T ₁ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by one weeding by 1 PW at 35 DAS)	4.42 (19.06)	5.85 (33.75)	6.87 (46.67)
T ₂ : one weeding by PW at 35 DAS	6.15 (37.34)	7.85 (61.10)	8.73 (75.69)
T ₃ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by Quizalofop-p-ethyl 10 % EC at 37.5 g a. i./ha at 20 DAS	4.18 (17.03)	5.71 (32.17)	6.12 (36.95)
T ₄ : farmers practice (2 IC at 20 & 40 DAS followed by 1 HW at 30 DAS)	3.25 (10.12)	4.26 (17.62)	4.92 (23.77)
T ₅ : one IC at 20 DAS followed by 1 HW at 30 DAS	3.42 (11.26)	4.37 (18.66)	5.01 (24.58)
T ₆ : weed free (3 HW at 15, 30 and 45 DAS)	2.12 (4.02)	3.29 (10.33)	4.33 (18.27)
T ₇ : unweeded control	6.51 (41.95)	8.91 (78.84)	9.29 (85.90)
SEm (±)	0.144	0.196	0.216
CD (p=0.05)	0.42	0.57	0.63

Note: DAS: days after sowing; HW: hand weeding; IC: inter-cultivation; PW: power weeder.

Weed control efficiency and weed index

Weed control efficiency (WCE) was significantly impacted by weed management techniques during the crop growth phase. With the greatest WCE was noted at every stage of observation, 90.46 % at 30 DAS, 86.92 % at 60 DAS and 78.75 % at harvest in weed-free treatment maintained through three manual weeding at 15, 30 and 45 DAS proved to be the most successful treatment (Table 4). This amply illustrated the benefit of consistent and prompt weed eradication in reducing weed pressure on crop. The farmers method, which involved two inter-cultivations at 20 and 40 DAS and one hand weeding at 30 DAS, was the next most successful strategy for weed control with WCE values at 30 DAS, 60 DAS and harvest noted as 76.00 %, 77.66 % and 72.34 %, respectively. Weed control efficiency values of 73.27 % at 30 DAS, 76.36 % at 60 DAS and 71.40 % at harvest were attained closely following this treatment with one intercultivation at 20 DAS and one manual weeding at 30 DAS.

The efficiency of various treatments was further demonstrated by the WI, which was computed based on the decrease in crop seed production. In terms of weed control methods, farmers method yielded the lowest WI (4.15 %), suggesting little yield loss as a result of successful weed suppression. One inter-cultivation at 20 DAS, one hand weeding at 30 DAS (7.59 %), pendimethalin at 1 kg a. i. ha⁻¹ as pre-emergence and quizalofop-p-ethyl at 37.5 g a. i. ha⁻¹ at 20 DAS came next (Table 4). On the other hand, one power weeding at 35 DAS and the unweeded control showed the higher WI values of 35.91 % and 57.83 %, respectively indicating significant yield decreases brought on by unrestrained weed development. Among the practical field-level approaches, the farmers method, comprising two inter-cultivations at 20 and 40 DAS along with one hand weeding at 30 DAS, proved to be

the next most effective treatment, recording WCE values of 76.00 %, 77.66 % and 72.34 % at 30 DAS, 60 DAS and harvest, respectively. A comparable level of efficiency was also observed with one inter-cultivation at 20 DAS followed by one hand weeding at 30 DAS, which resulted in WCE values of 73.27 %, 76.36 % and 71.40 % at corresponding stages. These findings indicate that integrated mechanical and manual weed control measures can effectively reduce weed pressure, although they are slightly less efficient than maintaining a completely weed-free condition. The effectiveness of weed management practices was further validated by the WI, which reflects yield reduction due to weed competition. The lowest WI (4.15 %) was recorded under the farmers method, indicating minimal yield loss owing to efficient weed suppression. This was closely followed by one inter-cultivation at 20 DAS combined with one hand weeding at 30 DAS (7.59 %) and the application of pendimethalin at 1 kg a. i. ha⁻¹ as pre-emergence followed by quizalofop-p-ethyl at 37.5 g a. i. ha⁻¹ at 20 DAS. These treatments effectively controlled weed growth and reduced biomass accumulation, thereby safeguarding crop yield.

In contrast, higher WI values were observed under one power weeding at 35 DAS (35.91 %) and the unweeded control (57.83 %), indicating substantial yield losses due to severe weed competition. The poor performance of these treatments may be attributed to delayed or inadequate weed control, allowing weeds to establish and compete with the crop during early growth stages. In contrast, higher WI values were observed under one power weeding at 35 DAS (35.91 %) and the unweeded control (57.83 %), indicating substantial yield losses due to severe weed competition. The poor performance of these treatments may be attributed to delayed or inadequate weed control, allowing weeds to establish and compete

Table 4. Effect of integrated weed management methods on weed control efficiency (%) at different growth stages and weed index (%) at harvest

Treatments	Weed control efficiency (%)		Weed index (%)	
	30 DAS	60 DAS	Harvest	WI (%)
T ₁ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by one weeding by PW at 35 DAS)	54.62	57.20	45.68	15.52
T ₂ : one weeding by PW at 35 DAS	-	22.50	11.89	35.91
T ₃ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by Quizalofop-p-ethyl 10 % EC at 37.5 g a. i./ha at 20 DAS	59.46	59.22	57.00	8.39
T ₄ : Farmers practice (2 IC at 20 & 40 DAS followed by 1 HW at 30 DAS)	76.00	77.66	72.34	4.15
T ₅ : 1 IC at 20 DAS followed by 1 HW at 30 DAS	73.27	76.36	71.40	7.59
T ₆ : weed free (3 HW at 15, 30 and 45 DAS)	90.46	86.92	78.75	-
T ₇ : unweeded control	-	-	-	57.83

Note: DAS: days after sowing; HW: hand weeding; IC: inter-cultivation; PW: power weeder.

with the crop during early growth stages.

Yield characters

The results clearly showed that integrated weed control methods had a major impact on sunflower seed yield, stover yield, harvest index and oil yield. The weed-free condition maintained by three hand weedings at 15, 30 and 45 DAS had the maximum seed yield of 2048 kg ha⁻¹, but seed yield varied significantly between treatments. This treatment was statistically comparable to farmers practices of two inter-cultivations at 20 and 40 DAS followed by one hand weeding at 30 DAS (1964 kg ha⁻¹), one inter-cultivation at 20 DAS followed by one hand weeding at 30 DAS (1893 kg ha⁻¹) and an integrated herbicidal treatment of pendimethalin at 1 kg a. i. ha⁻¹ as pre-emergence followed by quizalofop-p-ethyl at 37.5 g a. i. ha⁻¹ at 20 DAS (1877 kg ha⁻¹). The unweeded control, on the other hand, had the lowest seed yield (864 kg ha⁻¹). The weed-free treatment and farmers practice produced seed yields that were 137.03 % and 127.31 % higher, respectively, than the unweeded control. Under weed-free conditions, the maximum stover yield of 4343 kg ha⁻¹ was achieved, which was statistically equivalent to farmers practices (4215 kg ha⁻¹), one inter-cultivation at 20 DAS followed by one hand weeding at 30 DAS (4190 kg ha⁻¹) and pendimethalin followed by quizalofop-p-ethyl (4114 kg ha⁻¹) (Table 5). The unweeded control group had the lowest stover yield (2440 kg ha⁻¹). In comparison to the control, weed-free and farmers practice treatments raised stover yield by 78 % and 72.75 %, respectively. Weed-free environments yielded the highest harvest index (32.05 %), which was comparable to other weed management practices. The unweeded control had the lowest harvest index (26.15 %). Weed control techniques had no marked impact on oil content; however, pendimethalin and quizalofop-p-ethyl had the greatest oil content (40.39 %) and one power weeding at 35 DAS had the lowest oil level (38.99 %) (Table 5). The maximum oil output of 819 kg ha⁻¹ was reported under weed-free conditions, while there were considerable differences in oil yield between treatments. This treatment was comparable to farmers practices (782 kg ha⁻¹), pendimethalin followed by quizalofop-p-ethyl (758 kg ha⁻¹) and one inter-cultivation at 20 DAS followed by one hand weeding at 30 DAS (749 kg ha⁻¹). At 343 kg ha⁻¹, while the unweeded control yielded the least quantity of oil. The oil yield increased by 138.78 %, 128 %, 121 % and 118.36 % under weed free situation in comparison to the control, weed-free, farmers practice, one inter-cultivation followed by hand weeding and pendimethalin followed by quizalofop-p-ethyl treatments.

Discussion

Weed flora associated

The abundance of sedges like *Cyperus rotundus* and *Cyperus iria*, as well as grassy weeds like *Cynodon dactylon*, *Dactyloctenium aegyptium*, *Eleusine indica*, *Digitaria ciliaris*, *Digitaria sanguinalis* and *Ischaemum rugosum*, emphasises the presence of narrow leaved weeds that are well suited to warmer climates. The greater percentage of broad-leaved weeds, such as *Alternanthera philoxeroides*, *Ageratum conyzoides* and *Heliotropium indicum*, highlights their ecological adaptability and capacity to display in a variety of environmental conditions. Soil characteristics, crop management practices and favourable meteorological environments that prevailed during the research period are all responsible for their dominance. The results of this study closely align with previous research that also showed a competitive and varied weed flora in sunflower-based systems. According to reports, broad-leaved weeds accounted for around 50–60 % of all weeds in sunflower fields, with grasses coming in second at 25–35 % and sedges at 10–15 % (11). *Ageratum conyzoides*, *Amaranthus spp.*, *Digitaria spp.* and *Cyperus rotundus* were among the key species they identified. They found that uncontrolled weed growth led to production loss by 35–55 %, especially when competition occurred during the early phases of crop growth stages.

Similarly, in another research it was observed that broad-leaved weeds constituted nearly 52–58 % of total weed density, while grasses and sedges accounted for 30–35 % and 10–12 %, respectively (12). According to their research, weed interference considerably decreased sunflower growth parameters and yield attributes between 20 and 40 DAS, which was the vital period of crop -weed competition. A similar pattern was also noted, with grasses accounting for 30–32 % of the overall weed flora and broad-leaved weeds for about 55 %. They added that, in comparison to unweeded control, effective weed management practices might lower weed density by 60–80 % and increase seed yield by 25–45 % (13).

Weed density

The recent study findings closely align with previous research, which highlighted the efficiency of ongoing weed control in lowering weed density and enhancing crop performance. The total weed densities were found to be as low as 5.0–6.5 m² at 30 DAS and 7.0–9.0 m² at later growth stages, compared to 15.0–22.0 m² in unweeded control plots, indicating that maintaining weed-free conditions by timely hand weeding significantly reduced weed population. They also

Table 5. Effect of integrated weed management methods on seed and stover yield, harvest index, oil content and oil yield of sunflower

Treatment	Seed yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	Harvest index	Oil content (%)	Oil yield (kg ha ⁻¹)
T ₁ : pendimethalin at 1 kg a. i./ha as pre-emergence followed by one weeding by PW at 35 DAS	1708	3907	30.42	40.24	688
T ₂ : one weeding by PW at 35 DAS	1313	3232	28.89	38.99	512
T ₃ : pendimethalin at 1 kg a. i. /ha as pre-emergence followed by Quizalofop-p-ethyl 10 EC at 37.5 g a. i./ha at 20 DAS	1877	4114	31.32	40.39	758
T ₄ : farmers practice (2 IC at 20 & 40 DAS followed by 1 HW at 30 DAS)	1964	4215	31.78	39.82	782
T ₅ : 1 IC at 20 DAS followed by 1 HW at 30 DAS	1893	4190	31.12	39.56	749
T ₆ : weed free (3 HW at 15, 30 and 45 DAS)	2048	4343	32.05	39.98	819
T ₇ : unweeded control	864	2440	26.15	39.68	343
SEm (±)	59.7	130.9	0.55	1.351	23.9
CD (p = 0.05)	174	381	1.60	NS	70

Note: DAS: days after sowing; HW: hand weeding; IC: inter-cultivation; PW: power weeder.

noted that broad-leaved weeds, grasses and sedges were all successfully controlled by weed-free treatments, yielding a 70–85% weed control rate (13). Unweeded plots, on the other hand, displayed continuous weed growth during the crop growth stages, which resulted in intense crop-weed competition and decreased yield. Unweeded control plots, on the other hand, showed dry matter buildup of 45–60 g m⁻² with higher weed densities (20–28 m⁻²) suggesting severe weed infestation (14). These quantitative results provide significant support for the recent findings, indicating that timely and consistent weed management approaches are necessary to successfully control a variety of plant species and reduce their competitive effect on crops.

Dry weight of weed

Weed emergence and development under favourable environmental conditions are further reflected in the gradual rise in weed dry weight from 30 DAS to harvest through treatments. The results of the current study closely align with the findings that demonstrated the significant impact of weed control techniques on dry matter accumulation and weed density. At various phases of crop growth, the weedy check in their study had the greatest weed density, ranging from 22.5–30.8 m⁻² (15). Moreover, it was noted that the lack of proper weed management produced favourable environments for constant weed emergence, quick development and increased biomass accumulation, all of which increased crop-weed competition. These quantitative data provide strong support for the present-day findings, demonstrating that weed growth and biomass accumulation are greatly suppressed by effective and ongoing weed control, while unweeded circumstances result in maximum weed density and dry weight (15).

Weed control efficiency

Different weed management practices have a significant impact on WCE during the crop growth phase. At each stage of observation, the weed-free treatment maintained by three hand weedings at 15, 30 and 45 DAS recorded the greatest WCE, with values of 90.46 % at 30 DAS, 86.92 % at 60 DAS and 78.75 % at harvest. This proves clearly how timely and constant weed suppression may reduce weed density and improve crop production. The variance in WCE among the treatments emphasises how critical timely and broad weed control techniques are for inhibiting weed development. These results show that carefully planned weed management activities are more successful than less intense methods in lowering weed biomass and density.

The WI, which shows yield decline as a result of weed competition provided supplementary data of the efficacy of weed control practices. The farmers approach had the lowest WI (4.15 %), indicating little crop loss due to effective weed control. By reducing biomass accumulation and efficiently controlling weed development, these treatments increased the crop yield. Higher WI values, on the other hand, were seen under one power weeding at 35 DAS (35.91 %) and the unweeded control (57.83 %), suggesting significant yield losses as a result of intense weed competition. Delayed weed management, which permits weeds to new growth and compete with the crop during early growth stages, may be the cause of these treatments' poor efficacy. Overall, the results closely match those of earlier research, which shown that timely and efficient weed management practices significantly lower biomass and weed infestation, improving WCE and minimising production losses (16). In disparity, unweeded control plots showed significantly higher WI values exceeding 50 % due to unchecked weed growth. According to earlier research, the

weed-free treatment had the highest WCE (80.5 %), as well as the highest seed yield (1980 kg ha⁻¹) and oil yield (752 kg ha⁻¹). These findings suggest that improved productivity was a result of effective weed biomass suppression and decreased crop-weed competition under weed-free conditions (17).

Yield characters

The results of the present study clearly indicate that integrated weed management practices exerted a significant influence on seed yield, stover yield, harvest index and oil yield of sunflower. The highest seed yield (2048 kg ha⁻¹) was recorded under the weed-free treatment maintained through three hand weedings at 15, 30 and 45 DAS. This superior performance can be attributed to the complete elimination of weed competition throughout the crop growth period, ensuring uninterrupted availability of essential resources such as nutrients, moisture, light and space during critical growth stages. However, this treatment was found to be statistically at par with farmers practice (1964 kg ha⁻¹), one intercultivation at 20 DAS followed by one hand weeding at 30 DAS (1893 kg ha⁻¹) and the integrated herbicidal approach involving pendimethalin as pre-emergence followed by quizalofop-p-ethyl at 20 DAS (1877 kg ha⁻¹). The substantial increase in seed yield under weed-free (137.03 %) and farmers practice (127.31 %) treatments over the control clearly demonstrates the importance of timely weed control in minimising crop-weed competition, particularly during the critical period of crop establishment. A similar trend was observed in stover yield. The increased stover yield under effective weed management practices may be attributed to enhanced photosynthetic efficiency and better biomass accumulation due to reduced competition. Although differences among managed treatments were statistically comparable, the improved harvest index under weed-free conditions indicates more efficient partitioning of assimilates towards economic yield.

Oil content remained relatively unaffected by different weed management treatments, suggesting that it is primarily governed by genetic and environmental factors rather than weed control practices. Oil yield, being a function of both seed yield and oil content, followed trends similar to seed yield. The marked increase in oil yield under effective weed management treatments further confirms the role of timely weed control in enhancing overall crop productivity. According to study, the weed-free treatment (two hand weedings at 20 and 40 DAS) produced the highest seed yield of (2251 kg ha⁻¹), along with improved growth parameters and a decreased weed population. These results closely match the recent findings, which showed that the weed-free treatment produced the highest seed yield (2048 kg ha⁻¹) (16). According to research, weed-free conditions produced the highest seed yield (1980 kg ha⁻¹) and oil yield (752 kg ha⁻¹), which were statistically equivalent to integrated weed management practices like inter-cultivation followed by hand weeding and herbicide-based methods (17). This result supports the present study, which found that the weed-free treatment was statistically equivalent to farmers practices, inter-cultivation + hand weeding and pendimethalin followed by quizalofop-p-ethyl. Maintaining weed-free conditions led to increased oil yield (761 kg ha⁻¹) and seed yield (1943 kg ha⁻¹), as well as better WCE (90.35 %). These findings are consistent with the present results and highlight the importance of keeping the crop free from weeds during critical growth stages to realise better productivity (18). Additional study found that integrated herbicidal treatments (oxadiargyl followed by hand weeding) produced a seed yield of 1962 kg ha⁻¹,

which was statistically comparable to the weed-free yield (2064 kg ha⁻¹) and associated with high WCE (92.6%) (19).

Regression Analysis Graph

The outcomes of the regression analysis clearly show a significant inverse relationship between sunflower seed yield and weed dry weight at harvest. According to the fitted linear regression equation, $Y = -15.584x + 2360.9$, the seed yield falls by 15.584 kg ha⁻¹ for each unit increase in weed dry weight (g m⁻²) (Fig. 1). The strong coefficient of determination ($R^2 = 0.9409$) indicates that the variation in weed dry weight accounts for around 94.09 % of the variance in seed yield. This shows a highly robust and consistent relationship, highlighting the fact that, under the specific experimental conditions, weed biomass is a significant factor determining sunflower output. The significance of keeping weed biomass low during the crop growth cycle, particularly during crucial phases of crop-weed competition, is further highlighted by the strong inverse relationship. Increased dry matter buildup from unchecked weed growth increases competition and drastically lowers production potential.

Conclusion

This field experiment suggests that weeds have a significant impact on the yield reduction of sunflowers (*Helianthus annuus* L.). The weed-free treatment produced the highest seed yield (2048 kg/ha) and oil yield (819 kg/ha), but it was statistically comparable to the farmers practices (1964 kg/ha and 782 kg/ha, respectively), one inter-cultivation at 20 days after sowing (DAS) followed by quizalofop-p-ethyl at 37.5 g a. i./ha at 20 DAS (1877 kg ha⁻¹ and 758 kg ha⁻¹, respectively). However, maximum benefit cost ratio (B:C) (1.97) was recorded from growing sunflower with weed management practice of pendimethalin at 1 kg a. i. ha⁻¹ as pre-emergence followed by quizalofop-p-ethyl 10 % EC at 37.5 g a. i. ha⁻¹ at 20 DAS, hence considered in addition to high yield is also economically more

remunerative option for growing sunflower. In order to confirm the uniformity and adaptability of integrated weed control practices, future research may focus on assessing them across various agro-climatic zones and soil types. To evaluate the effects of recurrent herbicide usage on microbial activity, soil health and the emergence of herbicide resistance in weed species, long term studies are required.

To create more sustainable and environmentally friendly weed management practices, it is also possible to investigate the combination of cover crops and biological weed control practices with current mechanical and chemical methods. Precision agricultural techniques like sensor-based weed identification and site-specific herbicide spraying may also improve weed control effectiveness while lowering input costs and environmental hazards.

Authors' contributions

The study was conceived, relevant materials were collected and the manuscript was written by the authors. Along with finalising the general organisation and scientific substance, the authors conducted a thorough analysis of the data gathered. L, DDP, AKS, ACD, SSM, DD, GP, NSS, ST, AM and A aided with the literature study, provided input on how the information was organised and made insightful recommendations that improved the research article. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

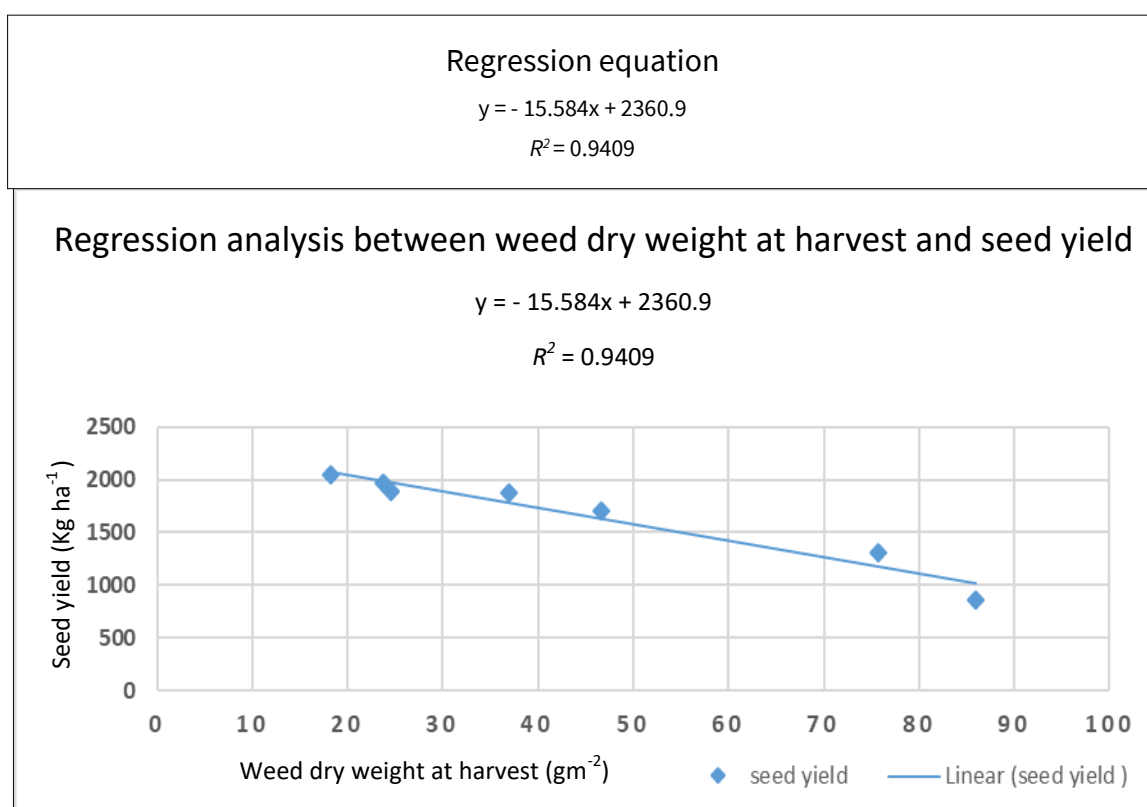


Fig. 1. Regression analysis between weed dry weight at harvest and seed yield.

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