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RESEARCH ARTICLE

Integrated Weed Management (IWM) for sunflower (*Helianthus annuus* L.) under modified spacing

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Abstract

The interaction between modified spacing and Integrated Weed Management (IWM) practices on weed dynamics, crop competitiveness and yield remains inadequately understood in sunflower cultivation particularly under diverse agro-ecological conditions. This gap necessitates systematic evaluation to develop spacing-specific IWM strategies for sustainable sunflower production. In the view of this, a three-year field study was conducted to evaluate the effectiveness of IWM practices on weed control, yield and soil health management of sunflower (*Helianthus annuus* L.) under modified spacing (75 cm × 25 cm) during the Rabi seasons (2021-22, 2022-23, 2023-24) at the Regional Agricultural Research Station (RARS), Nandyal, Andhra Pradesh. The study was carried out using the hybrid NDSH 1012 to assess the long-term impacts of weed management strategies on crop performance and sustainability. The experiment, laid out in a randomized block design (RBD) with seven treatments which includes integrated pre- and post-emergence herbicides, mechanical weeding, hand weeding and a weed-free check. The weed-free treatment (three hand weedings at 15, 30 and 45 days after sowing (DAS) recorded the lowest weed count (0.71-2.70 m^{-2}), highest weed control efficiency (WCE: 89.0-98.7 %) and maximum seed yield (2307 kg ha^{-1}). Pre-emergence pendimethalin (1.0 kg active ingredient ha^{-1}) followed by one power weeding with inter-row rotary power weeder at 35 DAS recorded 2216 kg ha^{-1} comparable to the weed-free check, with 77.2-90.2 % WCE and weed index (WI) of 4.9-10.1 %. Farmer's practice (two inter-cultivations + one hand weeding) recorded 2120 kg ha^{-1} with the highest net returns of ₹ 97595 ha^{-1} due to reduced labour cost. Soil microbial populations were unaffected by the treatments, indicating biological sustainability. Integrated weed management involving pendimethalin application with mechanical weeding is recommended as a cost-effective and eco-friendly weed control strategy for paddy-fallow sunflower cultivation in semi-arid India. This approach supports sustainable weed management while significantly reducing dependence on manual labour.

Keywords: economics; mechanical weeding; pendimethalin; weed control efficiency; weed dry matter; weed index; weed population

Introduction

Sunflower (*Helianthus annuus* L.) is one of the most important oilseeds crop globally, valued for its high-quality edible oil, wide adaptability and short growth duration (1). In India, sunflower contributes significantly to domestic edible oil production; however, because of several biotic and abiotic factors, its productivity is still below the global average (2, 3). Among the biotic factors, weed infestation is a major yield-limiting problem, capable of causing yield losses ranging from 30 to over 60 % depending on weed type, density and duration of competition (4). The critical period of weed competition in sunflower crop typically occurs within the first 20 to 40 days after sowing (DAS), during which uncontrolled weed growth can severely hinder crop establishment, nutrient uptake and photosynthetic efficiency (5, 6).

The weed flora in sunflower fields is highly diversified, often comprising competitive annual grasses such as *Echinochloa colona, Dactyloctenium aegyptium* and *Eleusine indica*, broad-leaved species including *Trianthema portulacastrum*, *Corchorus* spp., *Phyllanthus niruri* and perennial sedges like *Cyperus rotundus* and *Cyperus difformis* (7, 8). These weed species can significantly lower seed yield, oil content and total economic returns due to their heavy competition for resources. Despite their effectiveness, traditional sunflower weed control has mostly relied on mechanical and manual techniques like hand weeding and inter-cultivation, which are time-consuming, labour-intensive and becoming less feasible due to a lack of labour in rural areas (9).

The judicious application of herbicides offers an efficient alternative for controlling weeds during the early season in sunflower. A pre-emergence application of pendimethalin at approximately 1.0 kg active ingredient ha^{-1} has been found to offer effective weed control. However, sole reliance on chemical weed control can lead to shifts in weed flora, herbicide resistance and potential environmental concerns (10). Integrated weed management (IWM) combining chemical, cultural and mechanical weed management practices, has been recommended as a sustainable way to ensure season-long weed suppression, maintain biodiversity and optimize resource use efficiency (11).

Sunflower crop spacing is another important factor influencing crop-weed competition, where modified spacing patterns can alter canopy growth, light interception and soil coverage, thereby controlling the weed emergence and growth (12). In paddy fallow sunflower systems, where residual soil moisture is limited, optimising spacing and weed management practices becomes even more critical for achieving profitable sunflower production (13).

Understanding the substantial yield losses caused by weeds, the need for labour, cost-effective control measures and the herbicide overuse concern, the present field experiment was conducted to evaluate different IWM strategies under modified spacing in sunflower crop. In order to identify efficient, cost-effective and ecologically safe methods for producing paddy-fallow sunflower in Andhra Pradesh, the study aimed to assess the efficacy of various IWM strategies on weed dynamics, yield performance and soil microbial activity.

Materials and Methods

A field experiment was carried out during three consecutive Rabi seasons (2021-22, 2022-23 and 2023-24) at the Regional Agricultural Research Station (RARS), Nandyal, under Acharya N.G. Ranga Agricultural University (ANGRAU), Andhra Pradesh, India. The experimental field is geographically located in a semi-arid zone with a clayey soil texture of Vertisols. The field is geographically located at 15.464877° N and 78.474784° E. The average annual rainfall of the experimental location is 721.9 mm and the mean annual temperature is 26.7 °C. Pre-experimental soil test analysis as per standard procedures (14) revealed that the soil was low in available nitrogen (125 kg ha^{-1}), medium in phosphorus (38.1 kg ha^{-1}) and high in potassium (401 kg ha^{-1}). The experiment was laid out in a randomized block design (RBD) with seven treatments replicated thrice. The treatments were as follows:

- T_1: Pendimethalin at 1.0 kg active ingredient ha^{-1} (pre-emergence) + one mechanical weeding with a inter-row rotary power weeder (5 HP) at 35 DAS that cut and uproot weeds between rows
- T_2: One mechanical weeding with an inter-row rotary power weeder at 35 DAS
- T_3: Pendimethalin at 1.0 kg active ingredient ha^{-1} (pre-emergence) + quizalofop-ethyl 10 emulsifier concentrate (EC) at 37.5 g active ingredient ha^{-1} 10 EC at 37.5 g active ingredient ha^{-1} at 15-20 DAS
- T_4: Farmer's practice comprising two inter-cultivations at 20 and 40 DAS + one hand weeding at 35 DAS
- T_5: One inter-cultivation at 20 DAS + one hand weeding at 30–35 DAS
- T_6: Weed-free control (three hand weedings at 15, 30 and 45 DAS)
- T_7: Control (no weeding)

The sunflower hybrid NDSH 1012 was sown at a spacing of 75 cm × 25 cm. Land was prepared once with a disc plough (primary tillage), followed by two passes of a cultivator (secondary tillage). A uniform fertilizer dose of 75 kg N + 90 kg phosphorus pentoxide (P_2O_5) + 30 kg K_2O ha^{-1} was applied across all treatment plots. The entire dose of P_2O_5 and half of the dose of K_2O were applied as basal dose. Nitrogen was applied in equal splits as a basal dose and at 30 and 50 DAS, while the remaining potassium was top dressed at 50 DAS.

Herbicides were applied using a manually operated knapsack sprayer at a spray volume of 500 L ha^{-1}. Weed count (no. m^{-2}) and weed biomass (g m^{-2}) were recorded at 30 and 60 DAS using a 1 m^2 quadrat placed randomly at three locations per plot. Collected weed samples were initially shade-dried for 48 hr followed by oven-drying at 65 °C to determine dry biomass.

Weed biomass and crop yield data were used to determine the weed index (WI) and weed control efficiency (WCE) according to standard procedures. Plant height, capitulum diameter, number of seeds per capitulum, 100-seed weight and seed yield were measured at physiological maturity. Soil microbial population was estimated using the serial dilution and plating technique (15) employing nutrient agar, potato dextrose agar (PDA) and actinomycetes isolation agar for enumeration of total bacteria, total fungi and total actinomycetes respectively. Weed control efficiency was calculated using the following formula (16).

$$\text{WCE (\%)} = \frac{\text{WCC - WCT}}{\text{WCC}}$$

Where, WCC is the weed count (number m^{-2}) in the control (unweeded) plot and WCT is the weed count (number m^{-2}) in the treated plot. The units of WCC and WCT are the same.

Weed index is a parameter derived from the crop yields obtained across the treatments of weed control research (17). It measures the crop yield loss accrued across treatments in comparison to a weed free plot or in certain cases the minimum weed-infested plot like two or three hand weeding (as good as weed free check) adopted in an experiment. It is the ultimate parameter towards appraisal of the superiority or inferiority of several treatments and is worked out in almost all weed control research.

$$\text{WI (\%)} = \frac{\text{YWF - YT}}{\text{YWF}}$$

Where, YWF is the crop yield in the weed free plot and YT is the crop yield in the treated plot. The units of both YWF and YT are the same.

Statistical analysis

The collected data were subjected to statistical analysis using analysis of variance (ANOVA) for a RBD with seven treatments and three replications (18). Necessary transformations ($\sqrt{x}$ + 1) were applied to weed count and biomass data to normalize variance prior to statistical analysis.

Results and Discussion

Weed count/m^2 at 35 days after sowing in sunflower

Significant differences in weed population were observed across treatments at 35 DAS during all three years (2021-22, 2022-23 and 2023-24) of experimentation (Table 1). The most common weeds observed in the field experimental plots were grasses like *E. colona* (jungle rice), *E. indica* (goosegrass), *D. aegyptium* (crowfoot grass), broad-leaved weeds such as *T. portulacastrum* (horse purslane), *Corchorus spp.* (wild jute), *P. niruri* (stonebreaker), *Chrozophora rottleri* (safflower spurge) and sedges such as *C. rotundus* (purple nutsedge) and *C. difformis* (small flower umbrella sedge). Over the period of the three years of experimentation, there were notable differences in weed counts between treatments.

The treatments T_1 and T_3 were the most effective herbicide-based treatments, reducing total weed counts to 7.41-2.73 m^{-2} and 11.37-2.88 m^{-2} respectively, across the years of study. The lowest weed counts (0.71-1.0 m^{-2} across all weed categories) were recorded under Treatment T_6, which involved three hand weedings at 15, 30 and 45 DAS, during all three years of study. It has been shown that the pre-emergence activity of pendimethalin on broad-leaved weeds and grasses, along with the post-emergence control of quizalofop-ethyl 10 EC at 37.5 g active ingredient ha^{-1} (which targets grasses), significantly reduced weed pressure. Treatments T_4 and T_5 showed moderate efficacy, while T_7 recorded the highest infestation (316.7, 101.1 and 57.1 m^{-2} total weeds in respective years), confirming the heavy competition posed by unchecked weed growth.

A thorough analysis of the treatments showed that T_1 and T_3 maintained consistently lower weed population throughout the crop growth period. This combined effect could be attributed to the complementary action of pendimethalin on germinating grasses and broad-leaved weeds through inhibition of mitotic activity and the post-emergence efficacy of quizalofop-ethyl 10 EC at 37.5 g active ingredient ha^{-1} against later-emerging grasses. The mechanical disruption at 35 DAS further enhanced aeration and light interception, suppressing weed regrowth. Similar results were observed, with season-long weed control in oilseeds achieved through combined pre- and post-emergence herbicide applications (19). Integrated weed management that included pre-emergence pendimethalin along with either mechanical weeding or a selective post-emergence herbicide proved highly effective in checking the growth of grasses, sedges and broad-leaved weeds in sunflower. Maintaining lower weed pressure during the early stages allowed the crop to use available soil moisture and nutrients more efficiently, which reflected in better plant growth and canopy development. The longer weed-free period supported greater dry matter accumulation and improved formation of the sunflower heads. Consequently, the treatments that managed weed consistently produced larger heads, better seed filling and higher yields, indicating a clear link between weed suppression and improved productivity under semi-arid Vertisol conditions.

Weed count/m² at 60 days after sowing in sunflower

Table 2 presents the weed count (number m^{-2}) at 60 DAS in sunflower. The weed count was generally lower in effective treatments at 60 DAS than at 35 DAS but increased in less effective ones. The lowest weed count (1.0-2.70 m^{-2} total) was observed in T_6, which showed steady suppression over the course of the crop growth period. Treatments T_1 and T_3 were superior among the chemical treatments, reducing total weed density to as low as 3.62–4.71 m^{-2} .

From the results, it is evident that the T4 and T5 treatments exhibited intermediate levels of control (Table 1 & 2). The mechanical weeding operations in these treatments likely disturbed the weeds but allowed partial regrowth due to the absence of residual herbicidal protection. Treatment T_6 exhibited near-zero weed counts, while T_7 demonstrated exponential weed growth (up to 316.7 weeds m^{-2}), emphasizing the highly competitive pressure of weeds under paddy fallow moisture conditions. This could be attributed to the mechanical disruption of weeds during inter-cultivation and hand weeding operations, which temporarily reduced weed pressure. However, the absence of residual herbicidal activity in these treatments allowed subsequent flushes of weeds to emerge, particularly under the moist soil conditions of paddy fallows, where continuous soil moisture following puddled rice favours successive weed germination. As a result, these treatments provided only partial and short-term control. The significant reduction in weed populations in T_1 and T_3 at 35 DAS also caused the sustained weed suppression at 60 DAS, supporting the findings that early-season weed control is crucial for long-term management in sunflower systems (20).

Weed dry matter (g m⁻²), weed control efficiency and weed index at harvest in sunflower

Weed dry matter accumulation varied significantly among the treatments across all three years (Table 3). Treatment T_6 recorded the lowest weed dry matter (5.37, 1.02 and 7.3 g m^{-2} in 2021-22, 2022-23 and 2023-24 respectively) and the highest WCE (98.7-89.0 %) during all three years, indicating almost complete suppression of

Table 1. Effect of different weed management treatments on weed count (no. m-²) at 35 DAS in sunflower

Treatment	Weed count (no. m⁻²)											
	2021–22				2022–23				2023–24			
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total
T_1	3.98 (15.1)	4.91 (24.1)	3.96 (14.7)	7.41 (153.9)	1.97 (3.4)	2.26 (4.6)	2.43 (5.4)	3.73 (13.4)	1.67 (2.3)	1.52 (1.8)	1.84 (2.9)	2.73 (7.0)
T_2	6.52 (42.3)	6.31 (39.8)	9.76 (94.3)	13.29 (175.5)	5.97 (35.2)	3.1 (9.1)	6.91 (47.3)	9.59 (91.6)	3.76 (13.7)	1.97 (3.4)	6.15 (37.4)	7.41 (54.5)
T_3	5.16 (25.9)	5.75 (33.8)	8.38 (69.3)	11.37 (128.2)	1.89 (3.1)	2.42 (5.4)	2.57 (6.1)	6.56 (42.5)	1.61 (2.1)	1.70 (2.4)	1.94 (3.3)	2.88 (7.8)
T_4	4.54 (20.6)	4.32 (18.0)	1.82 (2.5)	6.48 (41.0)	3.53 (12)	1.95 (3.5)	2 (3.5)	4.42 (19)	1.97 (3.4)	1.76 (2.6)	2.58 (6.2)	3.56 (12.2)
T_5	5.27 (27.6)	5.50 (29.7)	8.13 (65.2)	11.11 (122.5)	3.70 (13.2)	1.79 (2.7)	2.61 (6.3)	4.76 (22.2)	1.78 (2.7)	1.89 (3.1)	2.48 (5.7)	3.46 (11.5)
T_6	1.0 (0)	1.0 (0)	1.0 (0)	1.0 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
T_7	8.96 (79.4)	9.79 (94.8)	16.89 (142.4)	17.82 (316.7)	6.65 (43.7)	2.32 (4.9)	7.26 (52.5)	10.08 (101.1)	3.78 (13.8)	2.07 (3.8)	6.32 (39.5)	7.58 (57.1)
SEm ±	0.11	0.22	0.13	0.33	0.06	0.09	0.08	0.15	0.09	0.06	0.09	0.21
C D at 5 %	0.34	0.65	0.29	1.03	0.18	0.27	0.24	0.44	0.27	0.18	0.27	0.43
CV (%)	12.6	13.9	11.4	13.0	12.4	11.5	10.8	12.5	10.7	12.5	13.2	12.0

Values outside parentheses are square-root–transformed means √(x + 0.5), while figures in parentheses represent the original weed counts (no. m-²). BLWs = Broad-leaved weeds; SEm = Standard error of the mean; CD = Critical difference; CV = Coefficient of variation.

Table 2. Effect of different weed management treatments on weed count (no. m-^{2}) at 60 DAS in sunflower

Treatment	Weed count (no. m^{-2})											
	2021-22				2022-23				2023-24			
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total
T_1	2.86 (7.3)	3.25 (9.6)	2.37 (4.6)	4.74 (21.4)	2.26 (4.6)	2.26 (4.6)	1.97 (3.4)	3.62 (12.6)	1.89 (3.1)	2.26 (2.6)	1.97 (3.6)	3.62 (9.3)
T_2	4.60 (20.5)	4.02 (15.2)	5.86 (33.4)	8.37 (69.1)	3.28 (10.3)	1.84 (2.9)	3.19 (9.7)	4.84 (22.9)	2.25 (4.6)	1.84 (2.2)	3.19 (4.4)	4.84 (11.2)
T_3	4.37 (18.2)	3.77 (13.3)	4.93 (23.3)	7.47 (54.8)	1.82 (2.8)	2.58 (6.2)	3.63 (12.7)	4.71 (21.7)	1.67 (2.3)	2.58 (3.1)	3.63 (6.8)	4.71 (12.2)
T_4	3.54 (11.6)	2.81 (7.0)	1.33 (0.8)	4.51 (19.4)	1.70 (2.4)	1.84 (2.9)	2.26 (4.6)	3.22 (9.9)	2.51 (5.8)	1.84 (2.0)	2.26 (2.2)	3.22 (10)
T_5	4.43 (18.7)	3.51 (11.4)	4.68 (21.0)	7.21 (51.0)	3.44 (11.3)	1.89 (3.1)	2.63 (6.4)	4.62 (20.8)	2.17 (4.2)	1.89 (4.1)	2.63 (4.6)	4.62 (12.9)
T_6	1.0 (0)	1.0 (0)	1.0 (0)	1.0 (0)	1.58 (2)	1.61 (2.1)	1.79 (2.7)	2.70 (6.8)	1.89 (3.1)	1.61 (3.3)	1.79 (3.5)	2.70 (9.9)
T_7	6.28 (38.4)	6.19 (37.4)	6.84 (45.9)	11.08 (121.7)	6.93 (47.6)	2.41 (5.3)	7.65 (58.1)	10.56 (111.0)	3.66 (12.9)	2.41 (4.9)	7.65 (41.3)	10.56 (41.3)
SEM ±	0.22	0.12	0.22	0.11	0.09	0.18	0.11	0.15	0.05	0.22	0.15	0.11
C D at 5 %	0.66	0.35	0.64	0.26	0.27	0.54	0.33	0.45	0.15	0.66	0.40	0.22
CV (%)	15.3	12.8	13.5	11.7	11.4	12.0	13.5	12.5	12.4	11.5	13.2	10.0

weed growth. The WI was recorded as 0 % in this treatment, signifying no yield loss due to weeds. With respect to herbicide-based approaches, T_1 achieved high WCE 77.2-90.2 % and low WI (4.9 -10.1 %), showing effective early-season and sustained weed suppression. T_4 also demonstrated good performance, with WCE ranging from 69.0 to 80.8 % and low WI of 1.0–6.44 %, highlighting the effectiveness of repeated inter-cultivation combined with hand weeding for weed control in sunflower (21).

T_7 exhibited the highest weed dry matter (62.6-75.3 g m^{-2}) due to unrestricted weed growth throughout the crop period, resulting in dense weed population that competed intensely with sunflower for water and nutrients. Under such circumstances, weeds, being more aggressive and faster-growing than sunflower during early stages, dominated the canopy, intercepting most of the available light and nutrients, which not only increased weed biomass but also caused substantial yield reduction (WI 37.7-41.7 %). These results support the concept that effective, early and continuous weed control is critical for minimizing weed biomass and associated yield losses. Similar findings have reported that integrating pre-emergence herbicides with mechanical interventions substantially reduces weed dry matter accumulation and enhances WCE in oilseed crops (22).

Growth and yield attributes of sunflower

Plant height did not differ significantly among treatments, indicating that weed competition primarily affected reproductive growth and yield rather than vegetative growth. However, capitulum diameter, seeds per capitulum and 100-seed weight exhibited clear treatment effects (Table 4). T_6 produced the largest capitulum diameters (15.58-16.25 cm), highest seed numbers (981-1047 seeds/capitulum) and heaviest seeds (4.54-4.78 g), demonstrating the positive effect of reduced weed competition on sink size and seed filling. Treatment T_1 recorded values comparable to the weed-free control. T_4 also produced comparable yields, indicating that effective weed control in these treatments led to improved crop growth. Across all yield components, T_7 recorded the lowest values, i.e., capitulum diameter (10.77-14.17 cm), seed number (705-795) and seed weight (3.39-4.28 g), due to intense competition for moisture, nutrients and light during the critical stages of crop growth.

Seed yield of sunflower

Significant differences in seed yield were observed among weed management treatments across all three years and in the pooled analysis (Table 5). During the three years, T_6 recorded the highest yields (2530, 2274 and 2119 kg ha^{-1} in 2021-22, 2022-23 and 2023-24 respectively) with a pooled average of 2307 kg ha^{-1} which was statistically superior to all other treatments. Among the herbicide-based treatments, T_1 produced a pooled seed yield of 2216 kg ha^{-1}, which was comparable to the weed-free check. This indicates that the treatment effectively controlled weeds throughout the crop growth period.

T_4 also recorded higher yields (pooled mean of 2120 kg ha^{-1}) indicating that continuous repeated inter-cultivation and manual hand weeding can produce competitive yield levels when labour is available. The lowest yields were recorded in T_7 (pooled mean of 1399 kg ha^{-1}), representing a yield reduction of nearly 40 % compared to T_6. These findings are consistent with previous reports on the performance of chemical weed management in irrigated sunflower (23).

Economics of sunflower cultivation

Economic analysis of sunflower cultivation during Rabi season (2023

Table 3. Effect of different weed management treatments on weed dry matter (g m^{-2}), WCE and WI at harvest in sunflower

Treatment	Weed dry matter (g m^{-2})			WCE (%)			WI (%)		
	2021-22	2022-23	2023-24	2021-22	2022-23	2023-24	2021-22	2022-23	2023-24
T_1	5.40	7.19	7.4	77.2	87.0	90.2	10.1	4.9	9.2
T_2	22.17	20.2	31.5	51.8	63.5	58.1	29.6	26.3	27.9
T_3	18.93	19.55	36.9	59.6	64.7	50.8	20.9	12.9	15.0
T_4	11.70	10.63	23.1	79.8	80.8	69.0	6.44	1.0	4.2
T_5	18.13	17.16	28.8	68.6	68.9	65.1	22.92	19.1	17.6
T_6	5.37	1.02	7.3	98.7	98.2	89.0	0	0.0	0.0
T_7	62.6	55.32	75.3	0.00	0.00	0.00	37.7	39.1	41.7
SEM ±	1.95	0.66	1.67	3.21	4.16	2.34			
C D at 5 %	6.10	1.96	5.2	9.5	12.8	7.3			
CV (%)	16.34	13.34	9.57	14.3	13.5	6.72			

Table 4. Effect of different weed management treatments on growth and yield attributes of sunflower

Treatment	Plant height (cm)			Capitulum diameter (cm)			Seeds/ capitulum			100-seed weight (g)		
	2021-22	2022-23	2023-24	2021-22	2022-23	2023-24	2021-22	2022-23	2023-24	2021-22	2022-23	2023-24
T_1	176.5	168.3	171.5	14.79	15.13	15.57	950	941	1017	4.54	4.56	4.66
T_2	175.2	161.4	168.9	13.02	13.16	14.33	850	831	836	4.01	4.52	4.26
T_3	173	171.2	171.0	12.89	14.29	14.63	826	878	829	4.08	4.47	4.51
T_4	181	172.6	173.1	14.42	13.62	14.27	850	831	836	4.51	4.63	4.52
T_5	176.9	165.4	170.9	13.36	15.04	14.83	918	869	962	4.51	4.31	4.51
T_6	177.4	170.8	174.4	15.58	16.25	15.63	981	956	1047	4.54	4.59	4.78
T_7	150.4	143.7	166.1	12.55	10.77	14.17	778	705	795	3.5	3.39	4.28
SEM ±	25	25	2.44	0.3	0.4	0.21	15	15	34.07	0.1	0.1	0.061
C D at 5 %	NS	NS	NS	0.9	1.28	0.65	44	49	106	0.3	0.3	0.19
CV (%)	11.5	11.5	2.02	12.8	11.6	12.43	14.8	13.6	6.47	13.9	12.4	12.34

NS: Non-significant

Table 5. Effect of different weed management treatments on seed yield of sunflower

Treatment	Seed yield (kg ha^{-1})			
	2021-22	2022-23	2023-24	Pooled data
T_1	2367	2251	2030	2216
T_2	1780	1675	1527	1660
T_3	2001	1981	1802	1928
T_4	2274	2163	1924	2120
T_5	1950	1839	1746	1845
T_6	2530	2274	2119	2307
T_7	1576	1386	1236	1399
SEM ±	65	73	98	55
C D at 5 %	203	219	306	163
CV (%)	12.9	13.5	9.6	11.5

-24) revealed that weed management significantly influenced the profitability of sunflower production (Table 6). The highest gross returns were recorded in T_6 at ₹ 105950 ha^{-1}, followed closely by T_4 at ₹ 101500 ha^{-1} and T_1 at ₹ 96200 ha^{-1}. However, the net income was highest in the T_4 at ₹ 97595 ha^{-1} which might be due to slightly low cultivation cost than T_6, owing to higher labour requirements. With respect to the benefit–cost (B:C) ratio, T_6recorded the highest value of 2.7, followed by $T_1$and T_4, each recording a value of 2.6. T_7 recorded the lowest economic performance, with net returns of ₹ 27903 ha^{-1} and B:C ratio of 1.8, reflecting both lower yields and reduced market returns. Integrated weed management not only improves yield but also increases profitability by optimizing input use efficiency (24) and the present results are in agreement with these findings. Although T_6 recorded the highest gross returns, T_4 achieved the highest net income due to its lower cost of cultivation. The weed-free treatment requires frequent hand weeding, which is highly labour-intensive and increases the cost of cultivation. In contrast, T_4 involved inter-cultivation followed by one hand weeding, effectively controlling weeds at a much lower cost. Thus, the reduced labour requirement in T_4 resulted in higher profitability despite slightly lower gross returns, emphasizing the economic advantage of adopting cost-efficient weed management practices.

Soil microbial count

The soil microbial counts under different IWM practices in sunflower indicated no significant differences among treatments for any microbial group, at both the initial and final sampling stages (Table 7). In all the treatments, the populations of total fungi, total bacteria, total actinomycetes, *Pseudomonas fluorescens* and *Trichoderma* spp. mostly increased from initial to final sampling which indicates that sunflower cultivation and IWM practices have not adversely affected microbial count. In fact, slight increases in microbial counts could be attributed to improved rhizosphere conditions and organic matter turnover during the crop growth period which is in confirmation with the results recorded previously (5). This clearly shows that IWM offers a more sustainable alternative to sole herbicide use. By combining herbicide use (pendimethalin) with either mechanical or manual hand weeding, the overall herbicide use is minimised, thereby reducing the risk of chemical residues in the soil.

This diversified approach helps maintain more stable microbial activity and supports healthier soil processes compared with systems that depend heavily on repeated herbicide applications. As a result, IWM not only manages weeds effectively but also contributes to long-term soil health and environmental resilience in Vertisol-based sunflower production.

Conclusion

It can be concluded that the three-year field study on sunflower revealed that effective weed management significantly improves

Table 6. Effect of different IWM practices under modified spacing on the economics of sunflower during Rabi 2023–24

Treatments	Cost of cultivation (₹ ha^{-1})	Gross returns (₹ ha^{-1})	Net returns (₹ ha^{-1})	B:C ratio
T_1	37462	96200	58738	2.6
T_2	36539	76350	39811	2.1
T_3	36615	90100	53485	2.5
T_4	39550	101500	97595	2.6
T_5	37386	87300	49914	2.3
T_6	39518	105950	66432	2.7
T_7	33897	61800	27903	1.8

Table 7. Soil microbial counts recorded under different IWM practices with modified spacing in sunflower

	Initial					Final				
	Total fungi	**Total bacteria**	**Total actinomycetes**	***P. fluorescens***	***Trichoderma* spp.**	**Total fungi**	**Total bacteria**	**Total actinomycetes**	***P. fluorescens***	***Trichoderma* spp.**
T_1	3.1×10^3	3.9×10^6	2.3×10^4	2.93×10^5	0.94×10^4	4.6×10^3	4.1×10^6	3.1×10^4	3.10×10^5	1.12×10^4
T_2	3.1×10^3	3.5×10^6	2.0×10^4	2.23×10^5	0.85×10^4	4.4×10^3	4.0×10^6	3.1×10^4	3.13×10^5	1.05×10^4
T_3	3.2×10^3	3.2×10^6	2.1×10^4	2.09×10^5	0.86×10^4	4.5×10^3	4.2×10^6	3.2×10^4	2.94×10^5	1.16×10^4
T_4	3.5×10^3	3.9×10^6	2.1×10^4	2.1×10^5	0.87×10^4	4.6×10^3	3.9×10^6	3.9×10^4	2.6×10^5	1.09×10^4
T_5	3.3×10^3	3.3×10^6	2.1×10^4	2.2×10^5	0.90×10^4	4.4×10^3	4.3×10^6	3.5×10^4	2.8×10^5	1.15×10^4
T_6	3.2×10^3	3.5×10^6	2.1×10^4	2.14×10^5	0.91×10^4	4.6×10^3	4.3×10^6	3.6×10^4	3.2×10^5	1.18×10^4
T_7	3.2×10^3	3.2×10^6	2.1×10^4	2.16×10^5	0.85×10^4	4.5×10^3	4.8×10^6	3.1×10^4	3.18×10^5	1.20×10^4
SEM ±	0.64	0.97	1.06	0.79	0.52	0.87	0.95	0.94	0.99	0.81
C D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	10.7	11.6	12.7	10.9	11.6	12.7	9.1	8.9	10.7	10.1

NS: Non-significant

yield and profitability. In all the experimented treatments, the weed-free control (T_6) consistently provided the lowest weed count and biomass, WCE and maximum seed yield (2307 kg ha^{-1}). However, the labour-intensive nature coupled with high costs may hinder its practicality for large scale cultivation. Integrated approaches, particularly pendimethalin at 1.0 kg active ingredient ha^{-1} as pre-emergence + one mechanical weeding at 35 DAS (T_1) and pendimethalin followed by quizalofop-ethyl 10 EC at 37.5 g active ingredient ha^{-1} (T_3), demonstrated excellent WCE of 77.2-90.2 %. Farmer's practice (T_4) involving timely inter-cultivation and hand weeding also showed effective WCE which also presents a good equilibrium between weed control and net profitability (₹ 97595 ha^{-1}), making it economically viable where labour is available. With respect to soil microbial count, all the treatments demonstrated no adverse effect on soil microorganisms. Thus, IWM offers a practical and sustainable strategy for sunflower cultivation under diverse agro-climatic conditions. These findings reinforce the suitability of IWM as a sustainable strategy for sunflower cultivation and provide a sound basis for farmer adoption and policy-level promotion in semi-arid Vertisol regions. Further research is required to evaluate the long-term implications of IWM on shifts in weed flora and the stability of soil microbial communities. Multi-season and multi-location studies will help determine the resilience and broader applicability of these practices across diverse agro-ecological conditions.

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Authors' contributions

PS and KP designed the experiment and carried out the three-year field study (during the Rabi seasons of 2021–22 to 2023–24) at the Regional Agricultural Research Station, Nandyal, Andhra Pradesh, to evaluate integrated weed management (IWM) strategies for sunflower (*Helianthus annuus* L.) under modified spacing (75 cm × 25 cm) using hybrid NDSH 1012. MR performed the statistical analyses and drafted the manuscript. W provided valuable suggestions throughout the research and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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