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Sustainable integrated weed control strategies to reduce herbicide use in sunflower production

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Abstract

This research aims to develop integrated weed control strategies that can effectively reduce the quantity of herbicides used in cultivation of sunflower. To address the challenge of weed management in mechanized crop fields and mitigate the adverse effects on the ecosystem, an experiment with 10 treatments was arranged in randomized block designs and replicated 3 times. The treatments included combinations of herbicide application, band application of herbicide and power weeder weeding. The higher weed control efficiency (WCE) was achieved in a weed-free environment. Additionally, higher WCE was observed in the treatment where weeds were managed through band application of pendimethalin (38.7 capsule suspension (CS)) in the seed row as a pre-emergence method and weeding was done with a power weeder twice. These 2 treatments registered more than 90 % WCE due to lesser weed occurrence. The present investigation also registered higher grain yield under weed-free control (2212 kg/ha). It was tailed by Pre-emergence (PE) herbicide (1 kg/ha of Pendimethalin (38.7 CS)) in seed row after irrigation followed by (fb) power weeder twice (on 15-20 and 30-35 DAS), PE herbicide (1 kg/ha of Pendimethalin (38.7 CS)) in seed row before irrigation fb power weeder twice (on 15-20 and 30-35 DAS) and PE herbicide (1 kg/ha of Pendimethalin (30 EC)) in seed row after irrigation fb power weeder twice (on 15-20 and 30-35 days after sowing (DAS)). Based on the results, pendimethalin (38.7 CS) can also be applied either before or after irrigation, as it will not significantly lose its efficacy in controlling weeds. These findings have practical implications for sunflower cultivation, offering effective strategies for integrated weed control.

Keywords

Sunflower; Integrated weed management (IWM); band application of herbicide; power weeder

Introduction

Sunflower (*Helianthus annuus* L.) is one of the primary important edible oilseed crops in the world. It requires moderate cultivation activities and possess very high-quality oil, which is very much needed not only for consumption purposes but also for industrial applications, *viz*., chemical and cosmetics. Sunflower is a short-duration, deep-rooted, drought-resistant, photo- and thermo-insensitive crop with broad adaptability (1) and offers the potential for its cultivation to boost oilseed production. Oilseed crops were found to be major commercial crops in India. India leads the world in oilseed crop production and the industry centered around these crops plays a significant role in the nation's economy. 12-15 % of the world's planted oilseed area is in India, where vegetable oils account for 7-10 % of worldwide output and 9-10 % of the world's total edible vegetable oil consumption (2). At present, there is a severe crisis prevailing for sunflower oil, primarily due to its superior quality when compared to other vegetable oils because of the presence of more polyunsaturated fatty acids (PUFA).

Weeds compete with other production elements, including moisture, nutrients, light and space, which ultimately limit crop output, making them one of the main pressures on crop cultivation, among other considerations. In irrigated environments, weed competition presents a serious obstacle to output, mostly because of wider spacing and proper fertilizer application (3). Consequently, screening out the undesirable weeds must take precedence over all other activities aimed at boosting agricultural output (4). The low yield of sunflowers is caused by a number of factors, one of them being weeds, which pose a serious hazard and can reduce seed yield by as much as 45 to 55 % (5). The intensity of weed infestation in sunflower directly impacts the interactions between weeds and crops that are competitive, increasing yield losses (6).

Farmers control the weed infestation in the cropped areas through cultural methods, but it is also very difficult due to its limitations including high cost, non-availability of the workforce, unfavourable soil and climatic conditions for efficient and economical weed control. The use of chemicals to maintain a weed-free situation is becoming more prevalent in this situation. Unchecked weed growth in crops can lead to a 62 % loss in sunflower grain yield (7). Lush development of a variety of weed species, lowers the yield of grain due to reduced photosynthetic efficiency, dry matter production and partitioning to profitable portions (8). The scarcity and high cost of labour in Indian agriculture have led to a rise in the use of technical-grade herbicides (9). Intensive agricultural practices facilitated the growth of crop-related weed species and the predominant adaptability of herbicides for their management. The application of herbicides may cause the accidental extinction of a variety of organisms, including both targeted and non-targeted species, upsetting the ecosystem's delicate balance (10).

When cultural, mechanical and chemical weed control techniques are integrated into any crop, better management of all weeds is very effectively possible (11). Herbicide use should be part of an integrated strategy for controlling weeds in agricultural crops (12) in an economical way. Crop species, time and rate of herbicide application, band spraying width and inter-row cultivation pattern and frequency all affected the effectiveness of band herbicide treatment. Inter-row cultivation combined with band herbicide treatment systems did not result in an increase in weed presence or a decrease in crop yield, suggesting that this technique might be applied more widely in agricultural production systems (13).

At this juncture, the utilization of herbicides at optimal dosage (14), at the correct stage (15), selection of herbicides based on weed species occurrence and density (16) as well as crop rotation with other herbicides, are very much essential to reduce the ill effects of herbicides and to sustain the soil. Band application, one of the strategies, has long history of promising outcomes, but due to a variety of limitations and disadvantages, it is still not frequently practiced in crop cultivation. Band application of herbicides supports optimal weed control and reduction in herbicide use and numerous limitations and disadvantages, including the requirement for appropriate pedo-climatic conditions and the scarcity of spray equipment appropriate for spreading herbicide bands are the reasons for this (17).

New precision technologies, such as sensor-guided mechanical controls, offer the potential to reduce the need for chemical applications in agriculture while increasing productivity (18). The development of mechanical weed control methods is also becoming more and more significant in conventional agricultural systems (19), taking into account the preservation of the natural environment and the demands of the contemporary market for nutritious food (20). According to reports from other researchers, hand weeding can be reduced to 24 % and weed control efficiencies of 63-92 % can be achieved with integrated inter-row and intra-row mechanical weeding methods (21).

Hence, the present thrust of weed research is formulated to reduce the use of herbicide quantity in the field by application of herbicide in seed row zones alone and combining non-chemical methods, which are efficient, economical and eco-friendly. Herbicide application at seed row alone will also reduce its adverse effect on the system and will take care of crops where mechanization is very difficult. To overcome the limitation of band application of herbicide, the time of application of pre-emergence herbicide was evaluated in this study. Thus, if pre-emergence herbicide application is possible before the application of irrigation, combining mechanized sowing with band application of herbicides is possible.

Materials and Methods

The field experiment was carried out at the oilseeds farm of Tamil Nadu Agricultural University, Coimbatore. It is located at latitude 11.02° N and longitude 76.93° E and the site boasts a semi-arid and tropical environment. It is also at an altitude of 443 m above mean sea level. During the period of experimentation, the crop received a total rainfall (RF) of 50.60 cm on 16 rainy days; the mean maximum (T. Max) and minimum (T. Min) temperatures respectively, were 31.1 °C and 23.6 °C and the mean relative humidity (RH) ranged between 88 % and 53 % at forenoon and afternoon respectively. The average bright sunshine hour (SSH) during the study period was 3.4 to 7.9 h per day (Fig. 1). The experimental soil was sandy clay loamy with 7.8 pH, 0.6 dS/m electrical conductivity, 0.35 % organic carbon content, low in available nitrogen, medium in available phosphorus and high in available potassium. Urea, single super phosphate and muriate of potash fertilizers were used to meet the fertilizer requirement of sunflower crops based on the recommended Nitrogen, Phosphorus and Potash (NPK) dose *viz*., 60:90:60 kg/ha.

The experiment was laid out in randomized block design and replicated 3 times with the following treatments.

Notation	Treatments
T_1 -	Pre-emergence (PE) herbicide in seed row after irrigation (1 kg a.i./ ha of Pendimethalin (30 EC)) *followed by* (*fb*) power weeder twice (15-20 and 30-35 days after sowing (DAS))
T_2 -	PE herbicide in seed row before irrigation (1 kg a.i./ ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)
T_3 -	PE herbicide in seed row after irrigation (1 kg a.i./ ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (15-20 and 30-35 DAS)
T_4 -	PE herbicide in seed row before irrigation (1 kg a.i./ ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (on 15-20 and 30-35 DAS)
T_5 -	PE herbicide after irrigation (1 kg a.i./ ha of Pendimethalin (30 EC)) *fb* power weeder (30 DAS)
T_6 -	PE herbicide after irrigation (1 kg a.i./ ha of Pendimethalin (38.7 CS)) *fb* power weeder (30 DAS)
T_7 -	Power weeder twice (on 15-20 and 30-35 DAS)
T_8 -	PE herbicide after irrigation (1 kg a.i./ ha of Pendimethalin (30 EC)) *fb* hand weeding (on 30 DAS)
T_9 -	Weedless plot
T_{10} -	Weedy plot

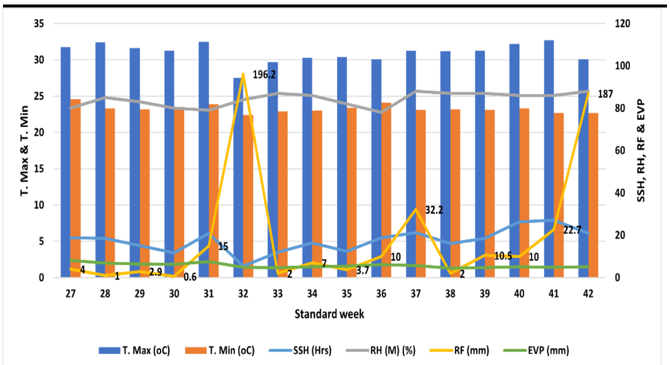
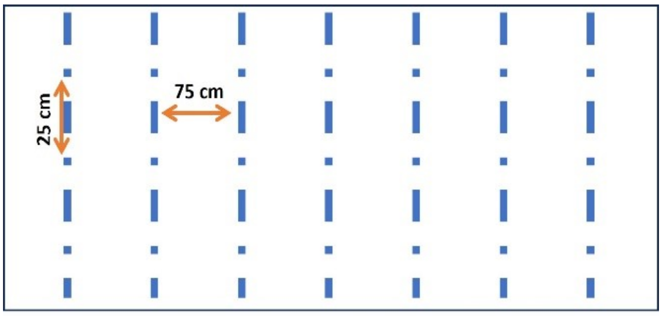


Fig. 1. Weather data during cropping period.

Spacing and sowing

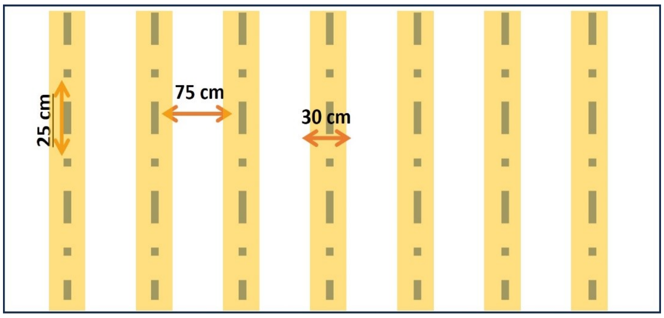
To maintain a 100 % population, sunflower hybrid seeds (Hybrid name; COH 3) were planted in the flatbed at a distance of 75 x 25 cm at 5 cm depth with 2 seeds per hill (Pic. 1). Later, the plants were thinned, leaving one healthy seedling per hill to maintain the 100 % population.



Pic. 1. Schematic diagram of crop geometry.

Spraying of herbicides

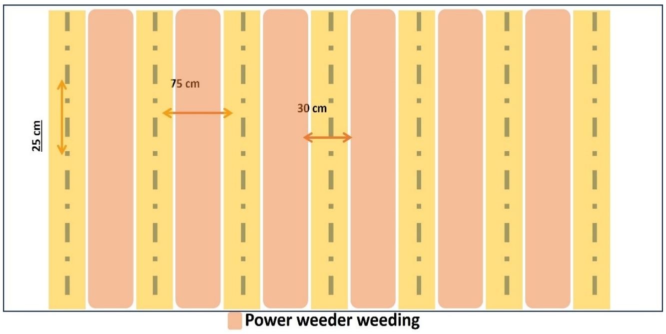
For treatments T_5, T_6 and T_8, a battery-operated backpack sprayer with a flat-fan nozzle was utilized to apply herbicide to the corresponding plots with spray volume of 500 L/ha. The herbicide was applied to the entire plot in treatments T_5, T_6 and T_8 and for treatments T_1, T_2, T_3 and T_4, herbicide was applied to the seed row only with a swath width of 30 cm (i.e. applied in 40 % area only) (Pic. 2 and 3). The herbicide was applied on 3 DAS in T_1, T_3, T_5, and T_8 and for treatments T_2 and T_4, it was applied immediately after sowing but before irrigation. After seeding, irrigation was started right away, followed by life irrigation on the fourth day and thereafter irrigation was continued whenever needed at a depth of 5 cm.



Pic. 2. Schematic diagram on placement of band application of herbicide.

Pic. 3. View of band application of herbicide plot.

Weeding A power-operated weeder with a 50 cm wheel track width and a 400 RPM centre drive rotavator with 12 blades was utilized for weeding while pulverizing the soil with rotational motion (Pic. 4 and 5). While operating, it ensured optimum moisture. The first power weeder weeding was done on 16 DAS and the second one was done on 30 DAS. Hand weeding was done with the help of labour using hand hoes. In the weedless plot, hand weeding was done at 15, 30 and 45 DAS to maintain a weed -free condition.



Pic. 4. Schematic diagram on operating space of power weeder.

Pic. 5. View of power weeder operation in experimental plot.

Recording observations

The gross plot size was 5.25 m x 4.75 m, with a net plot of 3.75 m x 4.25 m. The weed data were subjected to a square root transformation ($\sqrt{x+0.5}$) to normalize the distribution. The density and dry matter production (DMP) of weeds were measured from designated quadrants of 1 m^2 area.

Five tagged plants from each plot were used to determine plant height (cm), sunflower head diameter (cm) and the number of grains per capitulum. After harvesting the capitulum, the seeds were threshed and cleaned. Each treatment plot's yield of sunflower grain was weighed and expressed in kilograms per hectare (kg/ha). Quality parameters, test weight and volume weight were also analyzed.

Weed control efficiency (WCE) was calculated to assess the effectiveness of different weed control treatments (22).

The formula used to compute WCE is: WCE (%) = ((DMC – DMT) / DMC) × 100

Where,

DMC = Dry matter production of weeds/m^2 in weedy check.

DMT = Dry matter production of weeds/m^2 in the treatment to be compared.

The weed index (WI) is a per cent reduction in seed yield due to weed compared to the total yield of weed-free treatment. The index of weed was determined using the following formula (23).

Weed Index (%) = ((X – Y) / X)) × 100

Where,

X = Seed yield from weed-free plot.

Y = Seed yield from the treatment for which the weed index is to be determined.

Based on the current prices in Coimbatore for labour, input and implement hiring, the costs of cultivation for different treatments were calculated. The yield of sunflowers was multiplied by the price to determine the gross returns and the entire cost of cultivation was deducted to determine the net returns. The gathered data were subjected to an analysis of variance (ANOVA) at 0.05 probability for the randomized block design.

Results and Discussions

Effect of weed control measures on weed

The experimental weedy plot was primarily occupied by grassy weeds such as *Cyanadon dactylon* (L.), *Dactyloctenium aegyptium* (L.) and *Echinochloa colona* (L.); broad-leaved weeds such as *Trianthema portulacastrum* (L.), *Digera arvensis* (Forsk.) and *Parthenium hysterophorus* (L.) and sedge *Cyperus rotundus* (L.). *Trianthema portulacastrum* (L.), the most common dicot weed in the study, was found to be more common than sedges and monocots when weed density was compared species-wise. Similarly results of predominance of the dicot weeds than grasses in sunflower experiments were also reported (24).

All the weed management practices in the experimental field significantly reduced weed density and dry weight over the check (Table 1). Though efficacy varied between practices, weed-free checks registered lower weed data (density and dry weight) due to 3 hand weedings done at 15, 30 and 45 DAS (1.3 nos./m^2 at 60 DAS). If hand weeding was combined with herbicide application, the weed control performance was better (2.7 nos./m^2 at 60 DAS) than any other treatments. The treatments with herbicide application followed by power weeder weeding (T_1, T_3, T_4, T_5 and T_6) also showed significant weed control, with weed count less than 15 nos./m^2 at 60 DAS. However, when pendimethalin (30 EC) was applied as a band in the seed row before irrigation, followed by weeding with power weeder, no substantial improvement in performance was observed (29.3 nos./m^2 at 60 DAS). In treatments T_1 to T_4, herbicides were applied only in the seed rows (band application), followed by a power-operated weeder for weeding on 15-20 DAS and 30-35 DAS. Compared with the unweeded check, plots treated with herbicide registered only 30 % of weed density and approximately 20 % of the weed dry weight over the unweeded control.

The experiments' results clearly showed that applying pendimethalin as a pre-emergence agent in sunflower effectively controls weed establishment in the early stage of crop development. It has been reported that Pendimethalin works by inhibiting weed seedlings' cell proliferation and root growth (25) and also found that the initial batch of grass weeds did not germinate or establish itself after the application of pendimethalin as a pre-emergence herbicide (26).

Table 1. Weed density, dry weight, weed control efficiency (WCE) and weed index (WI).

Treatment	Weed density (Nos./m²)		Weed dry weight (g/m²)		WCE (%)	WI (%)
	30 DAS	60 DAS	30 DAS	60 DAS		
T_1 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	5.5 (29.3)	3.9 (14.7)	2.4 (5.1)	2.9 (8.1)	87.8	7.9
T_2 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	6.4 (40.0)	5.5 (29.3)	3.5 (11.6)	3.0 (8.8)	75.6	20.6
T_3 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (15-20 and 30-35 DAS)	5.3 (28.0)	3.5 (12.0)	2.3 (4.8)	1.8 (2.6)	90.0	2.9
T_4 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (on 15-20 and 30-35 DAS)	5.6 (30.7)	3.7 (13.3)	2.4 (5.3)	2.9 (7.9)	88.9	6.3
T_5 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder (30 DAS)	5.8 (33.3)	4.1 (16.0)	3.0 (8.7)	3.0 (8.3)	86.7	11.9
T_6 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder (30 DAS)	5.7 (32.0)	3.9 (14.7)	3.0 (8.4)	2.9 (8.2)	87.8	9.9
T_7 - Power weeder twice (on 15-20 and 30-35 DAS)	7.0 (48.0)	7.2 (50.7)	4.3 (17.6)	4.6 (20.8)	57.8	27.2
T_8 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* hand weeding (on 30 DAS)	5.9 (34.7)	1.8 (2.7)	3.0 (8.7)	1.1 (0.7)	97.8	12.1
T_9 - Weed less plot	4.9 (24.0)	1.4 (1.3)	2.2 (4.4)	0.9 (0.3)	98.9	0.0
T_{10} - Weedy plot	10.1 (101.3)	11.0 (120.0)	6.2 (37.8)	6.5 (42.4)	-	42.0
SEd	0.3	0.4	0.1	0.3		
CD (P=0.05)	0.6	0.9	0.3	0.5		

Figures in parenthesis are original values - Data transformed to $\sqrt{(x+0.5)}$

The control of weed emergence in the seed rows may be attributed to using pendimethalin in an entire area or a band application. Additionally, early-stage power weeder operations successfully managed the weeds between the rows. The weed control with the application of pendimethalin followed by power weeder weeding twice maintained lower weed density up to 60 DAS except in the treatment where pendimethalin (30 EC) was applied before irrigation in seed row followed by power weeder twice. It might be due to herbicide leaching or displacement from the seed row through irrigation water when irrigation was performed immediately after herbicide application.

Among the 2 formulations, efficacy was lower in Pendimethalin (30 EC) when applied before irrigation than in Pendimethalin (38.7 CS). However, applying Pendimethalin (38.7 CS) herbicide did not register significant differences before and after irrigation. Based on the results, pendimethalin (38.7 CS) can also be applied before irrigation, as it will not significantly lose its efficacy in controlling weeds. Using a power weeder for weeding without herbicide application had little impact on weed control (50.7 nos./m² at 60 DAS). This might be due to the reason that the power weeder worked only between the 2 rows and did not effectively control weeds in the seed rows.

To determine the efficacy of the weed management alternatives, the weed control efficiency (WCE) and weed index (WI) of the weed management options as a result of several weed management treatments were calculated. The higher WCE was achieved in a weed-free environment. Additionally, higher WCE was observed in the treatment where weeds were managed through band application of pendimethalin (38.7 CS) in the seed row as a pre-emergence method and weeding was done with a power weeder twice. These 2 treatments registered more than 90 % WCE due to lesser weed occurrence. When the weeds were managed with a power weeder alone (without herbicide application), lower WCE (57.8 %) was recorded due to the higher incidence of weeds, as weeds were not controlled in seed rows. It has also been observed that weeds in the row zone can significantly lower yields, sometimes by as much as 18-76 % (27-29). All weed management techniques successfully lowered the generation of dry matter from weeds, reassuring them of their effectiveness through WCE. A similar result (30) of herbicidal treatments with lesser weed dry matter than unweeded check treatment was reported in the earlier studies as well.

The application of Pendimethalin (38.7 CS) to the seed row after irrigation, followed by two rounds of weeding using power weeder, resulted in a notable reduction in the weed index, which was lowest at 2.9 %. This was attributed to the combined impact of the chemical and power weeder on weed control. With less crop weed competition in this treatment, crops yielded better, which resulted in a lower weed index. Compared to using chemical herbicides for an entire area, band applications were used only for 40 % of the area and the remaining area (60 %) was maintained with intercultural operations through a power weeder, which offers an environmentally acceptable alternative while simultaneously increasing economic return.

Therefore, sunflower crop cultivation with an altered spacing of 75 x 25 cm and application of pendimethalin (38.7 CS) as pre-emergence in the seed row after irrigation, followed by power weeder weeding (twice), which reduces weed density without affecting sunflower yield, offers promising improvements in sunflower cultivation. This instills confidence in the potential of these practices to brighten the future of sunflower farming.

Effect of weed control measures on sunflower crop growth

Various weed management strategies significantly impacted the growth parameters (Table 2), providing insight into the crop's resource utilization. In the present investigation, it was observed that taller plants (198.5 cm) were found in the weed-free condition, followed closely by the application of PE herbicide (Pendimethalin (38.7 CS)) in the seed row after irrigation, followed by the use of a power weeder twice (at 15-20 and 30-35 days after sowing). Additionally, taller plants were also found with the application of PE herbicide in the seed row before irrigation (Pendimethalin (38.7 CS)) followed by the use of a power weeder twice (at 15-20 and 30-35 days after sowing) and with the application of PE herbicide in the seed row after irrigation (Pendimethalin (30 EC)) followed by the use of a power weeder twice (at 15-20 and 30-35 days after sowing).

The key tools for analyzing growth are the measurement of leaf area index (LAI) and dry matter production (DMP) (Fig. 2). These parameters are essential for understanding the productivity of crops. A weed-free environment results in higher LAI and DMP, which are comparable to the effects of using herbicide with employing a power weeder. The same trend of results was also observed in all other growth parameters *viz*., crop growth rate (CGR) and relative growth rate (RGR) (Fig. 3) in all the stage of crop growth. The reason for this could be that the treatments mentioned earlier provided better weed control compared to the others. This allowed the crop to use light, water and nutrients more effectively (31). During the growth phase, there was intense resource competition, resulting in shorter plants in the weedy check. Similar reports of reduced plant height due to high weed infestation in sunflower have also been observed (32, 33).

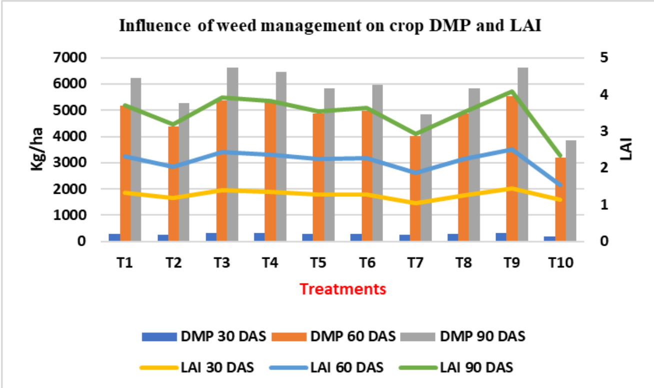


Fig. 2. Effects of weed management on sunflower crop growth.

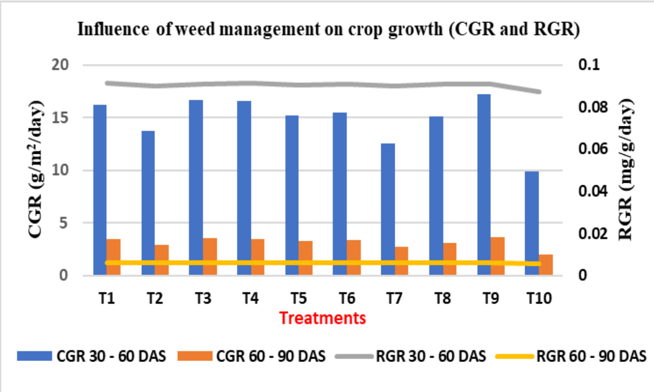


Fig. 3. Effects of weed management on sunflower crop growth.

Table 2. Effects of sunflower crop growth and yield parameters by weed management.

Treatment	Plant height at harvest (cm)	Days to 50 % flowering	100-grain weight (g)	Head diameter (cm)	Number of grains / Capitulum
T_1 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	192.2	53.0	4.6	28.3	965
T_2 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	177.3	52.1	4.5	25.9	847
T_3 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (15-20 and 30-35 DAS)	196.9	53.0	4.6	29.1	974
T_4 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (on 15-20 and 30-35 DAS)	195.9	53.0	4.6	28.9	971
T_5 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder (30 DAS)	190.5	52.3	4.5	27.8	907
T_6 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder (30 DAS)	190.7	52.7	4.5	28.2	935
T_7 - Power weeder twice (on 15-20 and 30-35 DAS)	169.4	52.0	4.3	22.7	730
T_8 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* hand weeding (on 30 DAS)	188.5	52.2	4.5	27.7	886
T_9 - Weed less plot	198.5	53.00	4.7	29.6	987
T_{10} - Weedy plot	151.4	51.93	4.3	18.6	512
SEd	15.6	0.62	0.1	2.1	60.1
CD (5 %)	32.9	NS	0.2	4.4	126.3

Furthermore, the power weeder's operation pulverizes the soil, promoting crop growth by ensuring proper aeration and mixing the soil for even distribution of nutrients from top-dressing fertilizer. Reduced weed competition and a favourable environment enabling crop growth, resulted in better growth and yield attributes.

The main factors influencing sunflower yield are the attributing factors for the yield. Weed control techniques have a positive impact on yield traits such as head diameter (cm), grain weight per capitulum, number of grains per capitulum, test grain weight and grain volume weight. During the critical stages of crop growth, reduced weed competition showed a favourable response with yield-enhancing traits. The head diameter size is one of the most crucial elements affecting sunflower yield. Higher head diameters (29.6 cm) were observed in the weed-free control, closely followed by the application of PE herbicide in the seed row after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) combined with power weeding twice (on 15-20 and 30-35 DAS) (29.1 cm), PE herbicide in the seed row before irrigation (1 kg/ha of Pendimethalin (38.7 CS)) combined with power weeding twice (on 15-20 and 30-35 DAS) (28.9 cm) and PE herbicide in the seed row after irrigation (1 kg/ha of Pendimethalin (30 EC)) combined with power weeding twice (on 15-20 and 30-35 DAS) (28.3 cm). This study also showed similar results in the number of grains per capitulum. Research suggests that the number of grains per capitulum, representing sunflower yield, is usually the yield component most affected by biotic and abiotic stresses (34, 35).

The study proves that effective weed control is crucial in creating a favourable growing environment for sunflower crop. This, in turn, allows the crop to make the best use of available resources, leading to higher growth and yield. The findings are consistent with previous research reports in sunflower (36). The study also suggests that increased translocation, a result of ideal growing conditions, leads to high source-to-sink conversion, thereby increasing yield attributes.

Effects of weed control methods on grain and oil yield of sunflower

The weed control methods significantly affected the production of grains from sunflowers (Table 3). The extent of weed infestation directly influences the level of competition between sunflower plants and weeds. In a weedy check, the grain yield decreased to 1284 kg/ha due to high weed infestation, resulting in a 42 % decrease compared to the weed-free control. Crops and weeds compete for water, light and nutrients. Consequently, crops in weedy areas cannot receive these essential elements in sufficient quantities, leading to poor yield. This observation supports the idea that weedy areas experience lower crop growth and yield due to the continuous presence of weeds during the growing season (37). When the period of weed competition was prolonged, the maximum sunflower grain production in the weed-free treatment exhibited a linear decrease (38).

Building on previous studies, our research further validates the impact of weed control methods on sunflower seed production. When there was no competition from weeds during the crop growth, the weed-free check resulted in a maximum seed production of 1840 kg/ha, compared to 518 kg/ha under the unweeded control in cluster beans (39). The current investigation also observed higher grain yield under weed-free control (2212 kg/ha). This was closely followed by the application of PE herbicide (Pendimethalin (38.7 CS)) in seed row after irrigation and the use of a power weeder twice (on 15-20 and 30-35 DAS). Additionally, PE herbicide in the seed row before irrigation (Pendimethalin (38.7 CS)) followed by the use of a power weeder twice (on 15-20 and 30-35 DAS), as well as PE herbicide in the seed row after irrigation (Pendimethalin (30 EC)) followed by the use of a power weeder twice (on 15-20 and 30-35 DAS) also resulted in high grain yield. It's important to note that oil yield is dependent on both seed yield and oil content. An increase in either of these factors leads to a higher oil yield due to the increasing sunflower grain yield. The lack of competition has the potential to improve the performance

Table 3. Yield, quality and oil yield influenced by weed management in sunflower crop.

Treatments	Grain yield (kg/ha)	Oil content (%)	Oil yield (kg/ha)
T_1 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	2038	43.8	892
T_2 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	1757	43.2	760
T_3 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (15-20 and 30-35 DAS)	2148	43.8	941
T_4 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (on 15-20 and 30-35 DAS)	2073	43.3	897
T_5 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder (30 DAS)	1949	43.3	845
T_6 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder (30 DAS)	1992	43.6	868
T_7 - Power weeder twice (on 15-20 and 30-35 DAS)	1610	43.5	702
T_8 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* hand weeding (on 30 DAS)	1945	43.5	846
T_9 - Weed less plot	2212	43.2	955
T_{10} - Weedy plot	1284	42.9	551
SEd	148	0.4	69
CD (5 %)	310	0.9	144

of both sources and sinks, promoting strong growth and physiological traits. This has led to improved yield characteristics such as head diameter (cm), grain weight per capitulum, number of grains per capitulum, test grain weight and grain volume weight, ultimately benefiting sunflower grain and oil yield.

Effect of weed control measures on sunflower economics

Any modification to the conventional crop-raising package should ultimately yield an economic benefit. While any system can be implemented to improve performance, it must be both practically feasible and economically viable from the farmers' perspective to be adopted in a large scale for crop cultivation. To determine the economic viability of various weed management treatments implemented in sunflower crop, gross returns, net returns and benefit-cost ratios were performed. Data presents the significant variance in net returns and benefit-cost ratios attained in the sunflower system as a result of the direct and indirect effects of various weed management strategies (Table 4). A higher gross return of India rupees (Rs.) 75208 was realized from weed-free control treatment in sunflower. Higher net returns of Rs. 18581 and benefit-cost ratio of 1.34 were enumerated in the treatment PE herbicide (Pendimethalin (38.7 CS)) in seed row after irrigation fb power weeder twice (on 15-20 and 30-35 DAS). This increase in net returns and the benefit-cost ratio could be attributed to the reduced cost of cultivation achieved by using chemical and a power weeder for weeding instead of manual labour as well as the optimal spacing for the power weeder to move without causing damage to the plant (40). The power weeder was found to be the most efficient option despite causing the highest per centage of weed injury and it was economical to use as compared to other treatments (41).

Conclusion

This clearly shows that applying the chemical in the seed row, followed by power weeding, not only meets the economic profit of sunflower cultivation but also provides an environmentally friendly option. Herbicide application in 30 cm bands resulted in a 60 % decrease in the amount of land sprayed, which in turn led to a significant reduction in the amount of herbicide used per hectare.

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Authors' contributions

ST, RK, Conceptualization and Methodology; ST, SN, KR, RL, SR, Investigation; ST, RL, SR, KR, NR, SK, SN, Data curation; ST, RL, SR, SN, Resources; ST, RL, SR, KR, SN, RK, Validation; ST, KR, RK, SN, Writing - original draft; NR, SK, Formal analysis; RL, SR, NR, SK, Writing - review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None.

Table 4. Impact of weed control measures on the economics of sunflower cultivation.

Treatment	Cost of cultivation (Rs./ha)	Gross Return (Rs./ha)	Net Return (Rs./ha)	B:C ratio
T_1 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	52279	69292	17013	1.33
T_2 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder twice (15-20 and 30-35 DAS)	54451	59738	5287	1.10
T_3 - PE herbicide in seed row after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (15-20 and 30-35 DAS)	54451	73032	18581	1.34
T_4 - PE herbicide in seed row before irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder twice (on 15-20 and 30-35 DAS)	54451	70482	16031	1.29
T_5 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* power weeder (30 DAS)	51951	66266	14315	1.28
T_6 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (38.7 CS)) *fb* power weeder (30 DAS)	51951	67728	15777	1.30
T_7 - Power weeder twice (on 15-20 and 30-35 DAS)	52279	54740	2461	1.05
T_8 - PE herbicide after irrigation (1 kg/ha of Pendimethalin (30 EC)) *fb* hand weeding (on 30 DAS)	56651	66130	9479	1.17
T_9 - Weed less plot	61679	75208	13529	1.22
T_{10} - Weedy plot	47279	43656	-3623	0.92

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