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RESEARCH ARTICLE

Effect of new generation herbicides on efficient weed management in lentil (*Lens culinaris* M.)

N Arumughan[1*], Karthick Vikram P[2], Kalaichelvi K[3], Saomya Dubey[4], Singireddy Prabhumitra Reddy[4], Lekhavarshinee J[5], D K Chandrakar[4] & G K Shrivastava[4]

[1]Department of Agronomy, Chaudhary Charan Singh Haryana Agricultural University, Hisar125 004, Haryana, India
[2]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Krishi Vigyan Kendra (KVK), Vridhachalam 606 001, Tamil Nadu, India
[4]Department of Agronomy, Indira Gandhi Krishi Vishwavidyalaya, Raipur 492 012, Chattisgarh, India
[5]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - arumughann918@gmail.com

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Abstract

Lentil, a low-maintenance hardy *rabi* pulse crop, often suffers severe yield losses due to weed infestation. New-generation herbicides are effective in weed management of pulses due to their dose requirement and broad-spectrum weed control capabilities. To evaluate the impact of these herbicides, field study was conducted at AICRP-Pulses Research Field, CoA, I.G.K.V, Raipur during the *rabi* season of 2023-24. The study aimed to assess the impact of new-generation herbicides on lentil growth, yield and weed suppression and to evaluate the crop's economic performance under different treatments. The experiment consisted 8 treatments including T1 (Pendimethalin (30 % EC) 750 g a.i. ha^{-1} PE), T2 (Imazethapyr (10 % SL) 50 g a.i. ha^{-1} PE), T3 (Pendimethalin (30 % EC) 750 g a.i. ha^{-1} PE *fb* Quizalofop-p-ethyl (5 % EC) 100 g a.i. ha^{-1} at 20 DAS), T4 (Oxyflourfen (23.5 % EC) 150 g a.i. ha^{-1} PE *fb* Propaquizafop (10 % EC) 100 g a.i. ha^{-1} at 20 DAS), T5 (Imazethapyr (10 % SL) 50 g a.i. ha^{-1} at 20 DAS), T6 (Quizalofop-p-ethyl (5 % EC) 100 g a.i. ha^{-1} at 20 DAS), T7 (Weedy check), T8 (Weed free check) with 3 replications laid out in Randomized block design. Broad-leaved weeds, particularly *Medicago denticulata*, dominated across growth stages. Results showed T8 had the lowest weed density and dry weight, followed by T4, while T7 recorded the highest. Similarly, WCI was maximum in T8 and T4, with WI showing the opposite. Economically, T8 achieved the highest returns, but T4 recorded the best benefit-cost ratio. Conversely, T7 yielded lowest returns and benefit-cost ratio.

Keywords: lentil; new generation herbicide; oxyfluorfen; propaquizafop; quizalofop-p-ethyl

Introduction

The pulses are the second most important crop type in India after cereals and play a remarkable role in the country's economy. Pulses are a rich source of fiber, protein, minerals and many vitamins (1). It's inclusion in daily diet is helpful in minimizing the risks of cardiovascular disease and Type II diabetes. Besides their nutritional value, pulses enhance soil productivity, improving yields of subsequent crops (2). There has been evidence of a 20-40 % increase in the yield of the successive crop (3). Thus, pulses are essential for achieving the nation's nutritional security. The per capita consumption of pulses has declined due to stagnant production caused by biotic and abiotic stresses, alongside a growing population. As per ICMR, a person should consume at least 65 g of pulses per day; however, the present per capita availability is only 47.1 g (4). According to previous researchers (5), despite being the largest producer of pulses, the internal demand cannot be fulfilled by domestic production alone due to the growing population. To meet this demand gap, India needs to rely on other countries, which has resulted in a price hike and reduced access for poor households (6). For a long time, the country's pulse shortage has been between 4 and 5 million tonnes, which has been supplemented by imports from nations like Canada, Australia, Myanmar, Russia, Turkey, Mozambique and Tanzania. However, the future appears bright for reaching pulse self-sufficiency given the recent successes in the past several years and the enormous potential for both vertical and horizontal expansion of pulse crops in India.

Lentil (*Lens culinaris* M.) can adapt to wider climatic and edaphic conditions. It is also considered as one of the world's most significant and ancient pulses. Lentil seed is an important protein source, especially in areas where it is often the only pulse crop that can be grown due to its hardiness under extreme edaphic and climatic conditions (7). In India, it is the most significant winter-planted legume after chickpea. It was observed that the cultivation of Lentil is more profitable under rain-fed conditions than other crops (8). However, lentil lacks the ability to compete with broad-leaved weeds and grasses, due to its less height, initial sluggish growth and longer duration, which affects the crop yield negatively.

Proper control of weeds is an important practice that determines the final yield (9). Weed-crop competition imposes significant physiological stress on crops by limiting essential resources such as nutrients, water and light, triggering various abiotic and biotic stress responses (10). Weed canopies intercept light, reducing crop photosynthesis and inducing stress signaling pathways. Weeds also absorb mineral nutrients more rapidly and in larger amounts than crops, enhancing their growth and competitive advantage for light, water and CO_2 utilization, which affects photosynthesis and water use efficiency (11).

These competitive stresses generate reactive oxygen species (ROS) and osmotic imbalance, activating adaptive defense mechanisms in crops (12). One key biochemical response is proline accumulation-an osmoprotectant vital for maintaining cellular osmotic balance, stabilizing proteins and membranes and safeguarding the photosynthetic apparatus (13). Under weed-induced stress, enhanced activity of the Δ^1-pyrroline-5-carboxylate synthetase (P5CS) pathway increases proline synthesis, mitigating oxidative stress and supporting chlorophyll stability, photosystem II function and stomatal regulation (13). Despite this adaptive response enabling survival under competition, crop yield still declines significantly due to sustained resource depletion caused by weed infestation. Weeds are reported to decrease lentil yields by 40-66 % (14). Especially, the broad-leaved weeds have become problematic in the initial crop growth period due to their fast growing and deep rooting ability. Timely control of weeds is critical in the first 50- 60 days after sowing (15). To obtain increased yield and higher revenue, a weed-free crop environment is essential. A 26-45 % yield increase in *rabi* pulses like chickpea, field pea and lentil has been recorded with proper weed management (16). Therefore, effective weed control is essential for maximizing lentil yield (17).

Anagallis arvensis, Chenopodium album, Cynodon dactylon, Euphorbia hirta, Melilotus alba and Xanthium strumarium are some of the most common weed species found in lentil crop (8). A weed-free crop environment is therefore necessary to achieve higher production and revenue. Thus, the most crucial element in assuring a high productivity of the lentil crop is weed management (17). The commonly adopted measure by the farmers is the manual weeding but now-a-days it is quite expensive because of low-availability of labour during the peak-season (18). Although hand weeding is effective in controlling inter-row weeds, it fails to eliminate intra-row weeds that grow close to crop plants, as removing them risks damaging the crop. Weed management using herbicides can be a sound solution for this problem. Among the existing herbicides, pendimethalin is commonly adopted as pre-emergence herbicide in pulse crops including lentil for a long time (8). Many pre-plant incorporated or pre-emergent herbicides can control weeds efficiently in the initial one month. This leaves the later emerging weeds unaffected as lentil is actually a long duration crop. There is little data on the application of post-emergence herbicides on this crop, particularly in India (19). Thus, it becomes necessary to test the effectiveness of new post-emergent molecules for the efficient management of lentil weeds.

Materials and Methods

Experimental site

The experimental trial was performed at AICRP-Pulses Research Field, CoA, I.G.K.V., Raipur (C.G.) during the *rabi* season of 2023-24 to study the best performing new-generation herbicide for weed management in the lentil crop. The soil type in the experimental site was clayey (*Vertisols*) with a slightly alkaline pH, normal EC, moderate organic carbon level, less available N, medium available P and medium available K.

Design and treatment details

The research trial was conducted in a randomized block design (RBD) with eight treatments, including the weedy check and weed-free check, each replicated three times.

T1 - Pendimethalin (30 % EC) 750 g ha^{-1} (PE)

T2 - Imazethapyr (10 % SL) 50 g ha^{-1} (PE)

T3 - Pendimethalin (30 % EC) 750 g ha^{-1} (PE) *fb* Quizalofop-p-ethyl (5 % EC) 100 g ha^{-1} (POE) at 20 DAS

T4 - Oxyfluorfen (23.5 % EC) 150 g ha^{-1} (PE) *fb* Propaquizafop (10 % EC) 100 g ha^{-1} (POE) at 20 DAS

T5 - Imazethapyr (10 % SL) 50 g ha^{-1} (POE) at 20 DAS

T6 - Quizalofop-p-ethyl (5 % EC) 100 g ha^{-1} (POE) at 20 DAS

T7 - Weedy check

T8 - Weed-free check (Hand weeding twice at 20 & 40 DAS)

Test crop

"CG Masoor 1" variety of lentil was used in the study. It is an early maturing variety with a duration of 88 to 95 days and is ideal for relay cropping especially under the semi-irrigated condition. It is suitable for both rainfed condition and relay cropping. It is suitable for both rainfed conditions and relay cropping. Released by IGKV, Chhattisgarh in 2020, this variety produces high biomass, making it a suitable choice for dairy farmers.

Crop management

The field was ploughed using a tractor drawn cultivator twice in criss -cross direction. It was then harrowed subsequently twice with the same tractor drawn cultivator to achieve loose and friable seed bed. Lastly, a planker was used to level the field, obtaining a gentle slope for irrigation. The fertilizer dose of N: P_2O_5: K_2O: S was applied at the rate of 20:40:20:20 kg ha^{-1} was applied manually before sowing. Urea, DAP, MOP and SOP were used to supply the required nutrients. The fertilizers were placed 5 cm below the seeds to protect the seeds from direct contact with the chemicals. Manual sowing of seeds (40 kg ha^{-1}) was done at 5 cm below the soil surface in furrows made by hand hoe with a row-row spacing of 25 cm. After the seeds were dropped, a thin layer of earth was always used to cover the furrows. Gap filling was carried out to maintain adequate plant population in all the experimental plots at 10 DAS with treated seeds where early sown seeds had not germinated. Intra-row spacing between the plants was kept 10 cm by thinning at 20 DAS in all the experimental plots manually wherever the plant population was dense. Irrigation was applied through the sprinkler method with the first irrigation given immediately after sowing to ensure adequate moisture for good germination and crop emergence and a second light irrigation was provided at the flowering stage especially to provide sufficient moisture for good flowering and pod formation.

Herbicide application and hand weeding details

Herbicides namely, Imazethapyr, Oxyfluorfen, Pendimethalin, Propaquizafop and Quizalofop-p-ethyl were sprayed according to the treatments. The quantities of the above-mentioned herbicides for the experimental plots were calculated using the formula mentioned below for each treatment, based on the rate of herbicide application and active ingredient available in commercial product (Table 1). The application rate and active ingredient of the chosen herbicides are mentioned in the treatment details. The water required to cover each plot (4.5 m x 4.0 m = 18.00 m^2) was calculated using the standard requirement of 500 L ha^{-1} and was found to be 0.9 l (900 mL). Before spraying, each plot's required dose of herbicides and water were carefully mixed. As the quantity of herbicides required is very less for individual plots, small measuring cylinder and reusable syringe were used to measure the required quantity of herbicides. The sprayer used was a battery-operated sprayer fitted with a flat spray nozzle. The sprayer was completely cleaned using soap powder and then washed with good water after spraying herbicidal treatment in all replications. Two HW were done using hand hoe at 20 and 40 DAS for the T8.

Quantity of commercial product required (kg ha^{-1}) =

$$\frac{\text{Rate of herbicide application (a.i.kg/ha)}}{\text{Active ingredient (\%) in the herbicide}} \times 100$$

Mechanism of action of the chosen herbicides

Imazethapyr

Imazethapyr inhibits the ALS or AHAS enzyme, an important enzyme necessary for the synthesis of isoleucine, leucine and valine (20).

Oxyfluorfen

Oxyfluorfen works by inhibiting the protoporphyrinogen oxidase (PPO) enzyme in plants, which ultimately results in lesser synthesis of chlorophyll (21).

Pendimethalin

Pendimethalin is a herbicide that works by preventing cell division and elongation in susceptible plants by binding to tubulin, a protein that's a major component of microtubules (22).

Propaquizafop

Propaquizafop works by inhibiting the fatty acids synthesis by binding to a target site protein in the weed called acetyl-CoA carboxylase (ACCase) and blocks it from functioning (23).

Quizalofop-p-ethyl

Quizalofop-P-ethyl also works by inhibiting the fatty acids synthesis through acetyl-CoA carboxylase (ACCase) by getting hydrolyzed into Quizalofop-P (acid form of Quizalofop-P-ethyl) (24).

Observations and measurements

Weed flora composition

Weed flora was observed at 30 days interval and at harvest stage. The observed weeds then grouped into grasses and broad-leaved weeds. The sedges category is skipped as no sedges were observed in the experimental site during the entire crop season.

Species-wise and total weed density

The species-wise weed density was observed at 30 days interval and at harvest stage randomly from two spots and a quadrate of dimension 50 cm * 50 cm (0.25 m^2) was used for this purpose. Only green weeds were taken as the sample. Weeds were counted species-wise in each plot and were added together to get the total weed density. The density of weeds was converted into m^{-2} for statistical analysis. As the weed density data had high variances, they were transformed by square root transformation i.e. $\sqrt{X+0.5}$ prior to performing an analysis of variance.

Species-wise and total weed dry weight

The species-wise weed dry weight were recorded at 30, 60, 90 DAS and at harvest stage. Weeds present inside the quadrate (0.25 m^2) were uprooted carefully with their roots intact. The roots of the samples were then cut and only the aerial parts were cleaned, sun-dried and finally oven-dried at 65 ± 5 °C for 48 hr. After thorough oven drying, the species-wise dry matter of each weed was recorded and were summed together to obtain the total dry matter of weeds in each treatment. The data were converted into g m^{-2} for statistical analysis. As the weed dry weight data had a lot of variances, they were transformed using square root transformation i.e. $\sqrt{X+0.5}$ prior to performing an analysis of variance.

Weed control efficiency

The WCE was estimated at 30 days interval and at harvest stage using the total dry weight of weeds in treated plots and weedy check plot as suggested by (25).

$$\text{WCE (\%)} = \frac{W_C - W_T}{W_C} \times 100$$

where

WCE = Weed control efficiency (%)

W_C = Weed dry weight in weedy check plot (g)

W_T = Weed dry weight in treated plot (g)

Yield attributes and yield

The attributes of lentil yield like number of pods $plant^{-1}$, number of seeds pod^{-1} and 100-seed weight were observed at the harvest stage of the crop. Seed yield and stover yield were estimated from the net plot area (3 m x 3 m = 9 m^2) after threshing, cleaning and drying and finally expressed in kg ha^{-1} using the conversion factor 1111.1. The conversion factor is obtained by diving the per ha area (10000 m^2) by

Table 1. Required quantity of commercial product for different treatments

Weed management	Quantity of commercial product required ha^{-1} (g or ml)		Quantity of commercial product required $plot^{-1}$ (g or ml)	
	PE	POE	PE	POE
T1	2500	-	4.5	-
T2	500	-	0.9	-
T3	2500	2000	4.5	3.6
T4	638.3	1000	1.2	1.8
T5	-	500	-	0.9
T6	-	2000	-	3.6
T7	-	-	-	-
T8	-	-	-	-

PE - Pre-emergence; POE - Post-emergence the net plot area (9 m^2). The harvest index (HI) is estimated by dividing the seed yield by the biological yield (Seed yield + Stover yield).

Weed index

Weed index was suggested by previous researchers (26). It expresses the yield reduction due to weeds in comparison with weed-free condition.

$$WI\ (\%) = \frac{\text{Maximum seed yield - Treated plot seed yield}}{\text{Maximum seed yield}} \times 100$$

Economics

The economics of lentil crop production for every treatment has been calculated. The cost of cultivation was computed using the available market prices during study for every treatment. Gross returns (Rs. ha^{-1}) was calculated by converting the yield into monetary terms using the prevailing market rate for every treatment. Net returns (Rs. ha^{-1}) was obtained by deducting cost of cultivation from gross returns. The B:C ratio was calculated with dividing the gross returns by the total cost of cultivation.

Statistical analysis

A statistical analysis was performed on the tabulated data pertaining to different parameters (27). The "F" test was used to assess the impact of the treatment. The treatments were compared by critical difference at the 5 % level of probability whenever the "F" test indicated significance. NS stood for non-significant results.

Results and Discussion

Floristic composition of weed

The various weed flora recorded at the experimental site are listed in Table 2. *Chenopodium album, Cichorium intybus, Echinochloa colona* and *Medicago denticulata* were the major weeds, while *Chrozophora rottleri, Melilotus indica* and *Physalis minima* were observed sparsely and can be grouped as minor weeds.

In addition to this, some weeds like *Alternanthera sessilis, Digera arvensis, Dinebra retroflexa, Parthenium hysterophorus, Portulaca oleraceae, Trianthema portulacastrum* and *Tridax procumbens* were observed in very less numbers. There were no sedges observed at the experimental site during the entire period of investigation. Several studies, including those by previous researchers (28-30), have identified dominant weed flora such as *Chenopodium album, Echinochloa colona and Digera arvensis* in lentil. These findings align with the results of the current study.

Weed density at 30, 60, 90 DAS interval and at harvest (No. m^{-2})

The effect of different weed management practices on total weed density in lentil at 30, 60, 90 DAS interval and at harvest were recorded and presented in Table 3. At 30 DAS, T8 was found to be the most effective weed control practice among all treatments. This was due to the proper control of weeds during the crop weed competition period, which ultimately resulted in improved crop growth and yield. Similarly, the weed study by previous researchers (31) also reveals that hand weeding resulted in effective control of weeds. Among herbicidal treatments, T4 and T3 effectively controlled weeds, particularly grassy species. This may be attributed to the wide window (used as both pre-emergent and post-emergent herbicide) and broad spectrum weed control ability (kills both annual broadleaf and grassy weeds) of Oxyflourfen in different crops (19). Along with oxyfluorfen, the post-emergence application of Propaquizafop showed a better control of the grassy weeds, which are the major weeds in lentil. In contrast, poor weed control and higher weed density were observed in the T7, followed by T6. The effect of different weed management practices on densities of *Echinochloa colona*, *Medicago denticulata*, *Cichorium intybus* and *Chenopodium album* in lentil at 30, 60, 90 DAS interval and at harvest were recorded and presented in Fig. 1-4 respectively. Similarly, the impact of different weed management practices on densities of *Physalis minima, Chrozophora rottleri, Melilotus indica* and other weeds in lentil at 30, 60, 90 DAS interval and at harvest were assessed and depicted in Fig. 5-8 respectively. Significantly lower densities of *Echinochloa colona*, *Chenopodium album*, *Cichorium intybus*, *Medicago denticulata* and other species were recorded under T8 compared to other treatments. Among the herbicides, T4 and T3 were more effective against both grassy and broad-leaved weeds, especially *Echinochloa colona* and *Medicago denticulata*, respectively. Conversely, the highest densities of *Medicago denticulata*, *Chenopodium album*, *Cichorium intybus*, *Echinochloa colona* and other broad-leaved weeds were noted under the T7. Broad-leaved weeds were predominant across all treatments; however, in the case of T2, the grassy weeds were comparatively more abundant. The order of dominance among the major broad-leaved weeds at 30 DAS was *Medicago denticulata* >

Table 2. Weed flora observed in the experimental field

S. No	Scientific name	Family	Common name
		Grasses	
1	*Echinochloa colona*	Poaceae	Barnyard grass
2	*Dinebra retroflexa*	Poaceae	Viper grass
		Broad-leaved weeds	
1.	*Alternanthera sessilis*	Amaranthaceae	Sessile joyweed
2	*Chenopodium album*	Amaranthaceae	Lamb's quarters
3	*Chrozophora rottleri*	Euphorbiaceae	Geiseler
4	*Cichorium intybus*	Asteraceae	Common chicory
5	*Digera arvensis*	Amaranthaceae	False amaranth
6	*Medicago denticulata*	Fabaceae	Toothed bur clover
7	*Melilotus indica*	Fabaceae	Indian sweet clover
8	*Parthenium hysterophorus*	Asteraceae	Congress grass
9	*Physalis minima*	Solanaceae	Sun berry
10	*Portulaca oleraceae*	Portulacaceae	Common purslane
11	*Trianthema portulacastrum*	Aizoaceae	Horse purslane
12	*Tridax procumbens*	Asteraceae	Coat buttons

Table 3. Effect of weed management practices on total weed density (No. m^{-2}) in lentil at different time intervals

Weed management practices	Total weed density (No. m^2)			
	30 DAS	60 DAS	90 DAS	At harvest
T1	**6.96** (47.94)	**7.96** (59.87)	**8.43** (70.58)	**10.46** (63.34)
T2	**7.55** (56.56)	**8.04** (64.23)	**8.92** (79.05)	**10.94** (75.29)
T3	**6.70** (44.43)	**7.33** (53.34)	**8.41** (70.15)	**8.23** (67.23)
T4	**4.23** (17.45)	**4.24** (19.22)	**4.59** (20.53)	**4.33** (18.23)
T5	**9.13** (82.82)	**9.79** (95.36)	**10.80** (116.2)	**9.84** (102.3)
T6	**9.76** (94.85)	**11.00** (120.6)	**12.07** (145.2)	**10.12** (137.4)
T7	**16.05** (257.2)	**17.02** (289.3)	**17.78** (315.5)	**11.09** (290.2)
T8	**0.71** (0)	**0.71** (0)	**3.14** (9.35)	**4.20** (18.36)
SEm ±	**0.24**	**0.28**	**0.32**	**0.93**
CD (p=0.05)	**0.73**	**0.85**	**0.97**	**2.81**

Figures in the parentheses are original values; data were transformed through $\sqrt{X+0.5}$ which are given in bold

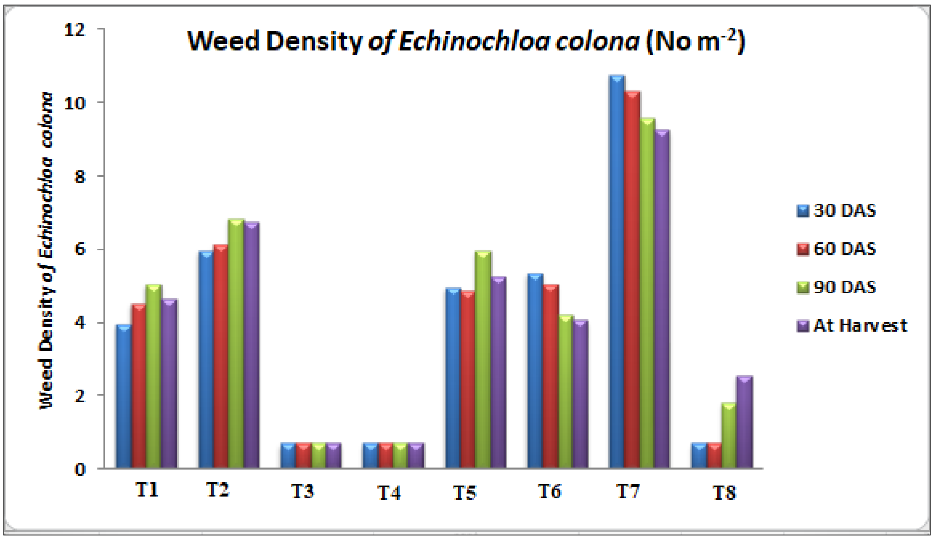

Fig. 1. Weed density of *Echinochola colona* (No. m^{-2}).

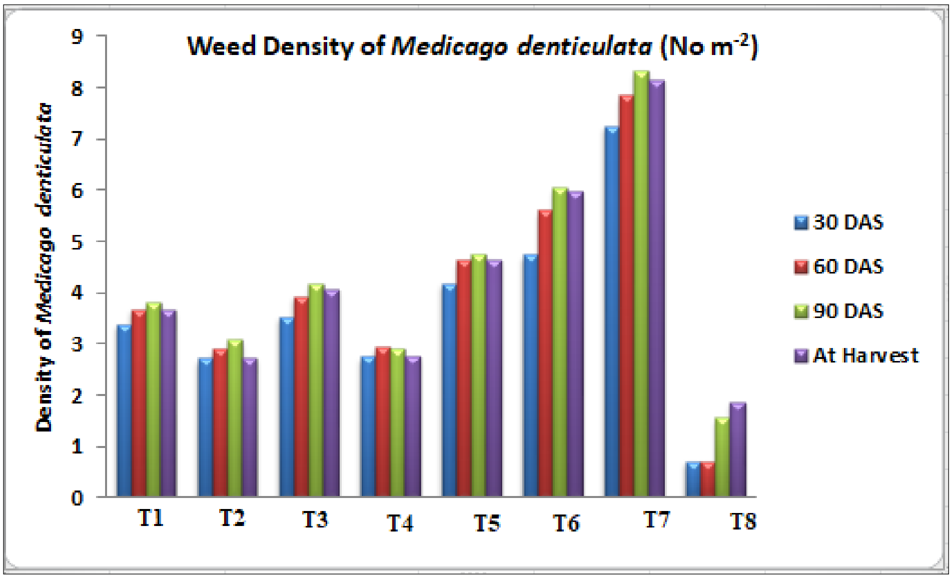

Fig. 2. Weed density of *Medicago denticulata* (No. m^{-2}).

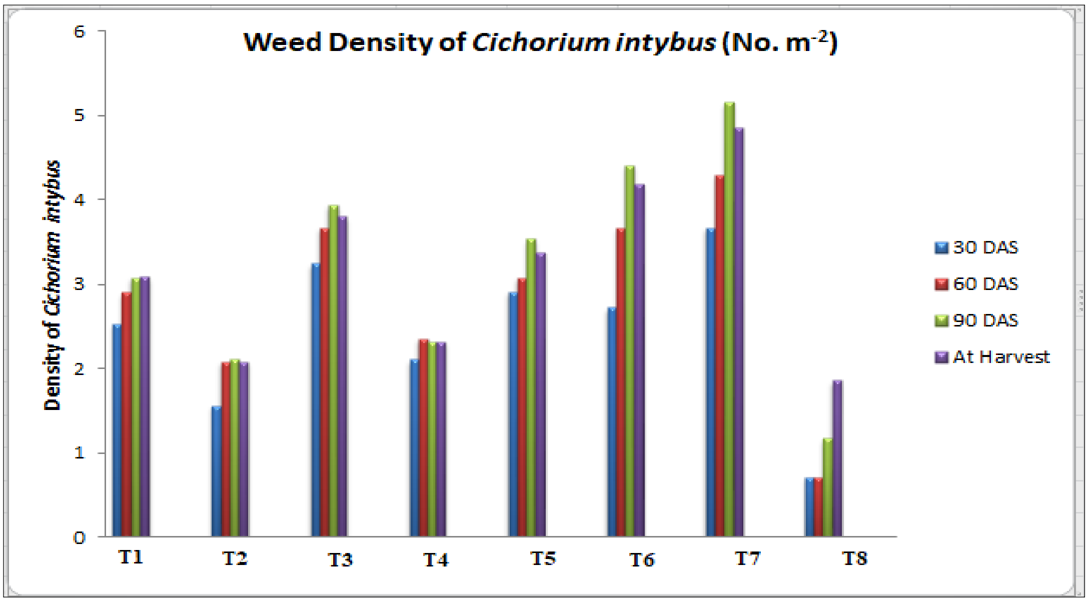

Fig. 3. Weed density of *Cichorium intybus* (No. m^{-2}).

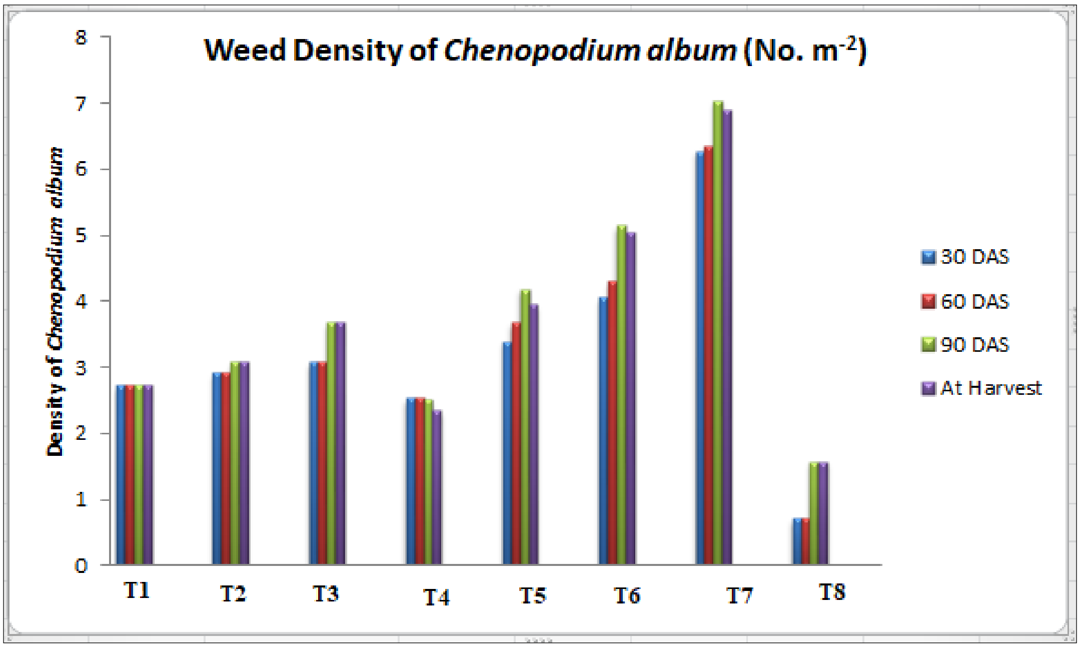

Fig. 4. Weed density of *Chenopodium album* (No. m^{-2}).

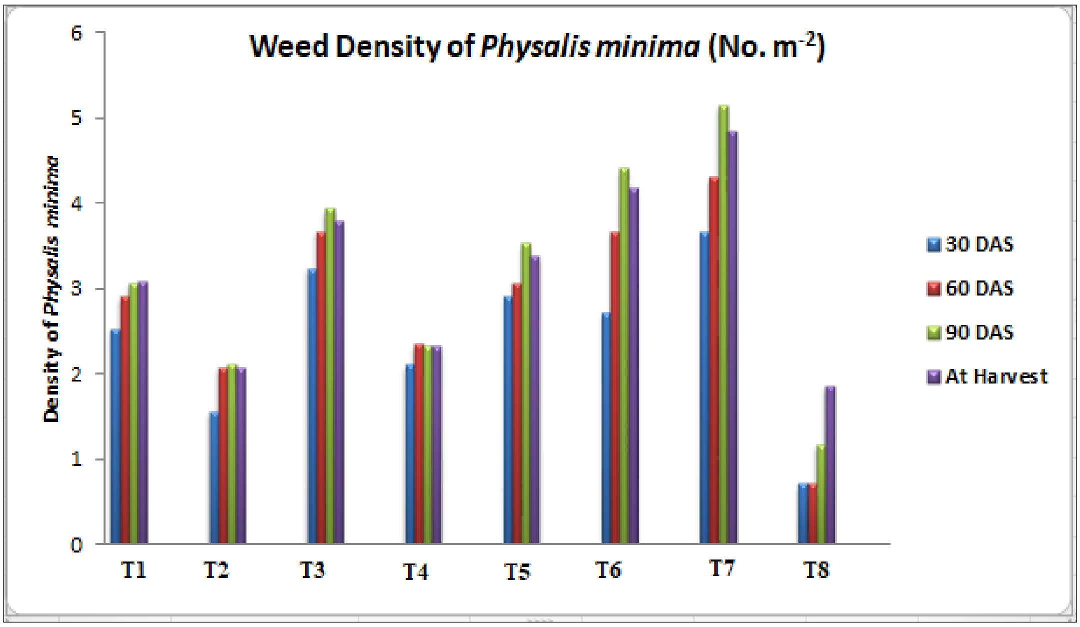

Fig. 5. Weed density of *Physalis minima* (No. m^{-2}).

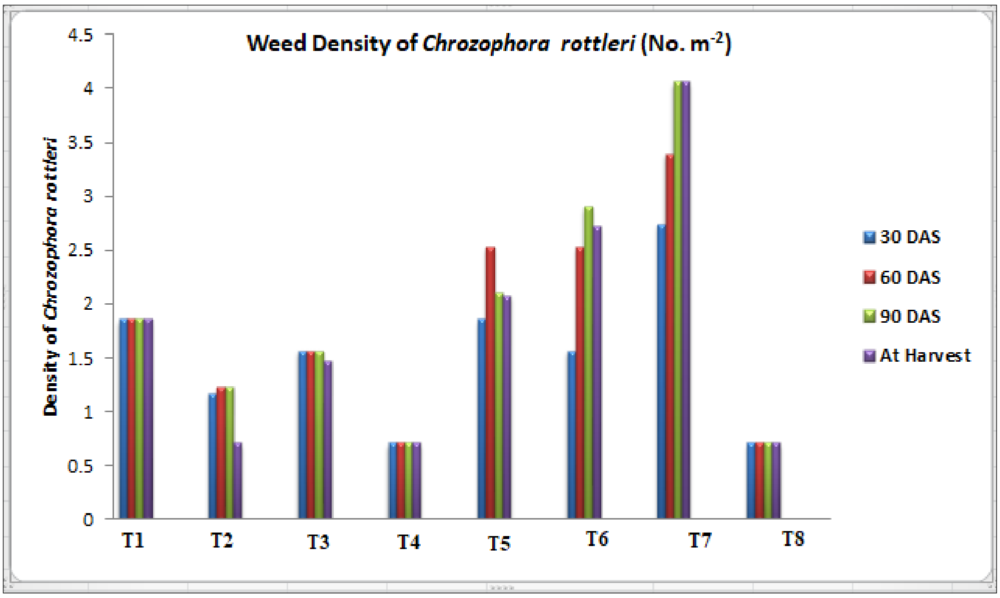

Fig. 6. Weed density of *Chrozophora rottleri* (No. m^{-2}).

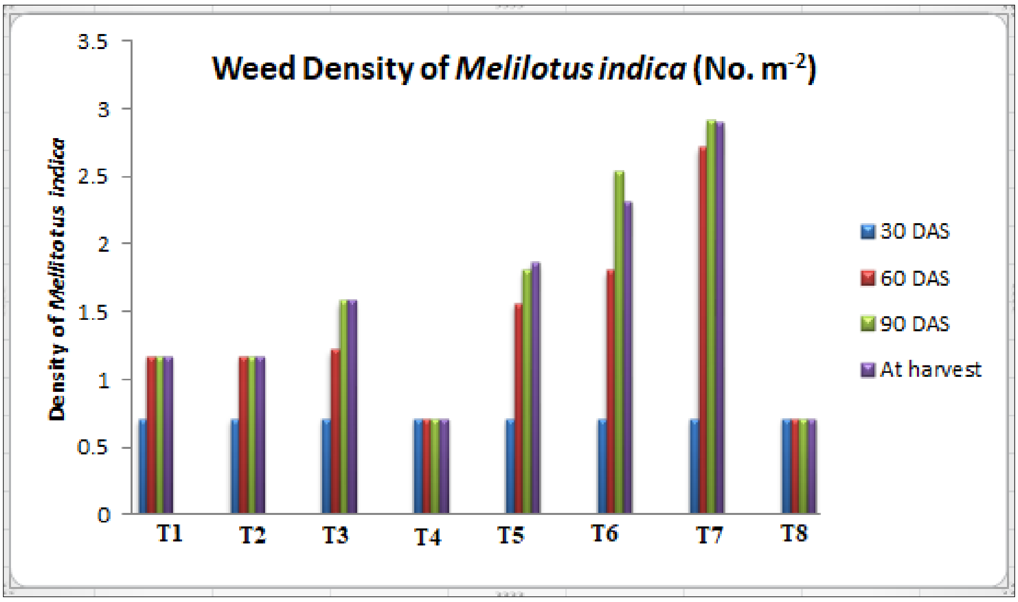

Fig. 7. Weed density of *Melilotus indica* (No. m^{-2}).

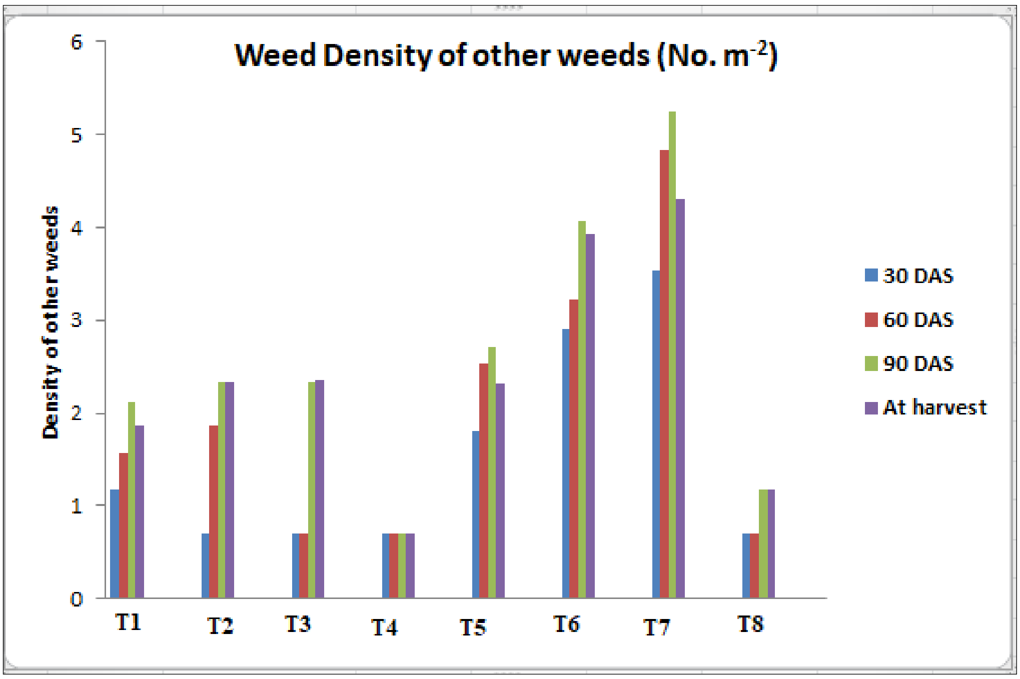

Fig. 8. Weed density of other weeds (No. m^{-2}).

Chenopodium album > *Cichorium intybus* > *Physalis minima* > *Chrozophora rottleri*. At 60 DAS, T8 recorded the lowest weed density among all treatments, followed by T4 and T3. The highest weed density observed in the T7 was attributed to the lack of timely weed management practices. Like 30 DAS, broad-leaved weeds remained dominant across all treatments except in T2, where grassy weeds prevailed. A greater diversity of weed flora was noted under T7, followed by T6. Effective control of grassy weeds at 60 DAS was achieved with T8, followed by T4 and T3. The density of grassy weeds under T6 decreased compared to 30 DAS, while poor control and higher grassy weed density were observed in T7 and T2. A slight decline in grassy weed density in T7 compared to 30 DAS was likely due to the smothering effect of rapidly growing broad-leaved weeds. The dominant broad-leaved weed species at 60 DAS followed the same order as at 30 DAS. *Melilotus indica* emerged after 30 DAS, possibly due to differential dormancy. Maximum control of broad-leaved weeds was obtained under T8, followed by T4 and T2. Poor control and higher densities of broad-leaved weeds were recorded in T7, followed by T6. Additionally, *Parthenium hysterophorus*, a newly emerging irrigated-land weed, appeared in patches at 60 DAS.

At 90 DAS, most weeds had reached peak vegetative growth and were transitioning to the reproductive stage, with no new weed emergence observed-likely due to depletion of viable weed seeds in the soil surface layer. This period coincided with lentil crop maturity, during which established weeds suppressed the emergence of new ones. Consistent with earlier observations, significantly lower weed density was T8, followed by T4 and T3. T7 recorded the highest weed density. Broad-leaved weeds remained dominant across treatments, except under T2, where grassy weeds prevailed. A diverse weed flora persisted in T7, followed by T6. Effective grassy weed control at 90 DAS was achieved with T4 and T3. Although T8 controlled weeds efficiently overall, it showed slightly higher grassy weed emergence than T3 and T4. The density of grassy weeds under T6 decreased compared to 60 DAS, whereas poor control was observed in T7 and T2. Grassy weed density in the weedy check (T7) continued to decline, likely due to suppression by fast-growing broad-leaved weeds. The order of dominance among broad-leaved weeds remained similar to previous stages, with *Cichorium intybus* becoming more prevalent due to its vigorous growth and competitive ability. Maximum broad-leaved weed control was achieved under T8, followed by T4 and T2, while poor control occurred in T7 and T6.

A general decline in total and species-wise weed density was observed at harvest, with a sharper reduction in grassy weeds across herbicidal treatments. The reduced density in T7 was likely due to interspecific competition and shading effects from mature weeds and crop plants. Conversely, a slight increase in weed density under T8 was attributed to reduced ground cover and greater light penetration after manual weeding. Like previous stages, the lowest weed density at harvest was recorded in T8, followed by T4 and T3, while the highest was in T7. Broad-leaved weeds dominated all treatments except T2, where grass prevailed. Grassy weeds were most effectively controlled under T4 and T3, while poor control persisted in T7 and T2. For broad-leaved weeds, maximum suppression was achieved with T8, followed by T4 and T2 and the least with T7 and T6.

Overall, the recorded data revealed that T7 consistently recorded the highest total and species-wise weed densities due to the absence of weed control measures, resulting in intense crop-weed competition and reduced yield. In contrast, T8 maintained the lowest weed densities throughout the growth period, ensuring effective weed suppression during the critical competition phase and promoting better crop growth and yield. The recorded result of weed density of this study aligned with the findings of previous studies (19, 32, 28). The application of oxyfluorfen as a weed management treatment effectively controlled annual broadleaf and grassy weeds during the early growth stages of chickpea as well as other pulses like lentil (33). The efficacy of weed control through herbicides propaquizafop, imazethapyr and clodinafop in chickpea was reported earlier (34). The findings proposed that propaquizafop along with imazethapyr and clodinafop were effective in reducing weed density and dry weight. Similarly, earlier studies reported that maximum weed density and minimum chickpea yield in weedy check treatment and vice versa in weed free check treatment (35). These results were in accordance with the findings of present study.

Table 4. Effect of weed management practices on total weed dry weight (g m^{-2}) in lentil at different time intervals

Weed management practices	Total weed dry weight (g m^2)			
	30 DAS	60 DAS	90 DAS	At harvest
T1	**2.70** (6.77)	**4.35** (18.43)	**6.25** (38.55)	**5.68** (31.73)
T2	**3.23** (9.95)	**5.32** (27.84)	**7.25** (52.12)	**6.95** (47.86)
T3	**2.40** (5.27)	**4.04** (15.81)	**5.91** (34.43)	**5.35** (28.17)
T4	**1.66** (2.25)	**3.20** (9.72)	**3.68** (13.07)	**3.35** (10.73)
T5	**3.61** (12.52)	**6.32** (39.43)	**8.46** (71.08)	**7.72** (59.07)
T6	**3.97** (15.25)	**6.93** (47.48)	**9.26** (85.21)	**8.63** (73.97)
T7	**6.24** (38.39)	**9.63** (92.25)	**11.14** (123.6)	**10.40** (107.7)
T8	**0.71** (0)	**0.71** (0)	**2.50** (5.73)	**3.24** (9.98)
SEm ±	**0.04**	**0.03**	**0.03**	**0.03**
CD (p=0.05)	**0.12**	**0.09**	**0.08**	**0.09**

Figures in the parentheses are original values; data were transformed through $\sqrt{X+0.5}$ which are given in bold

Weed dry weight at 30, 60, 90 DAS interval and at harvest (g m^{-2})

The data on total dry matter production of the weeds at 30, 60, 90 DAS and at harvest stage as influenced by different herbicide treatments are presented in Table 4. At 30 DAS, significantly lower dry matter production by weed species such as *Echinochloa colona*, *Chenopodium album*, *Cichorium intybus*, *Medicago denticulata* and others, along with the least total weed dry weight, was recorded under T8, followed by T4 and T3. The highest species-wise and total dry matter production was recorded in T7. T8 was most effective in suppressing grassy weed growth and dry matter accumulation, followed by T4 and T3, while poor control was observed in T7 and T2. For broad-leaved weeds, T8 recorded the greatest reduction in dry matter, followed by T4 and T2, whereas higher dry matter was observed in T7 and T6. The effect of different weed management practices on dry weights of *Echinochloa colona, Medicago dentuculata, Cichorium intybus, Chenopodium album* and other weeds at 30, 60, 90 DAS and at harvest stage as influenced by different treatments were presented in Fig. 9-13. Among broad-leaved weeds, *Medicago denticulata* and *Chenopodium album* accumulated the highest dry matter, followed by *Cichorium intybus*.

At 60 DAS, T8 recorded the lowest total and species-wise weed dry matter, followed by T4 and T3, while T7 recorded the highest values. T8 effectively reduced grassy weed dry matter accumulation, followed by T4 and T3. Poor control and higher grassy weed dry matter were observed in T7 and T2. Regarding broad-leaved weeds, maximum control was achieved under T8, followed by T4 and T2, whereas poor control was recorded in T7 and T6. *Medicago denticulata* and *Chenopodium album* exhibited the highest dry matter accumulation at 60 DAS, which was greater than at 30 DAS, indicating continued growth and dominance.

At 90 DAS, like earlier stages, significantly lower species-wise and total weed dry matter were recorded in T8, followed by T4 and T3, while T7 showed the highest accumulation. T8 effectively suppressed grassy weeds, followed by T4 and T3, whereas poor control occurred in T7 and T2. For broad-leaved weeds, maximum control was observed in T8, followed by T4 and T2. The highest dry matter of *Medicago denticulata* and *Chenopodium album* persisted at this stage, with other broad-leaved weeds also showing continued accumulation.

A general decline in total and species-wise weed dry matter was observed at harvest. However, a slight increase in weed dry

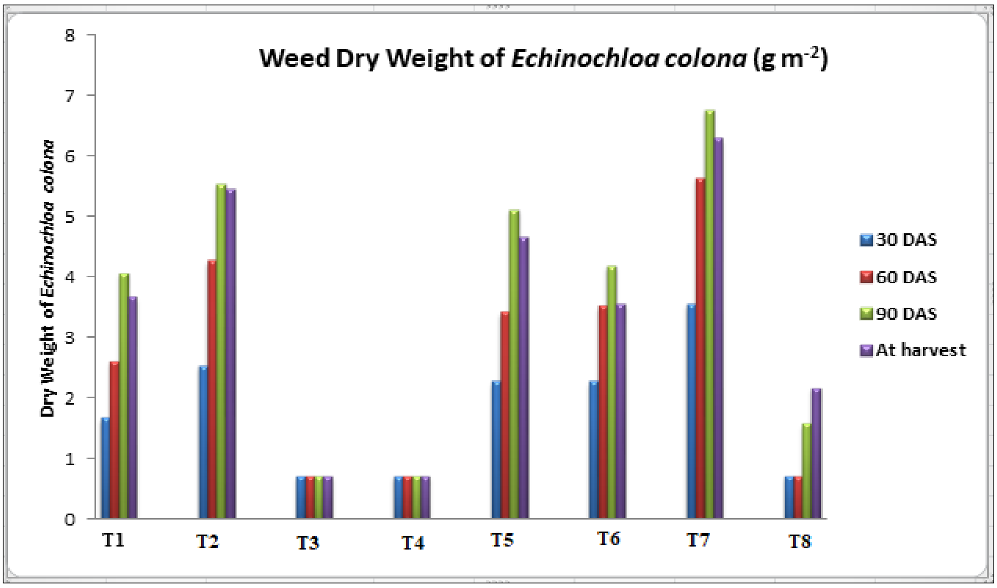

Fig. 9. Weed dry weight of *Echinochloa colona* (g m^{-2}).

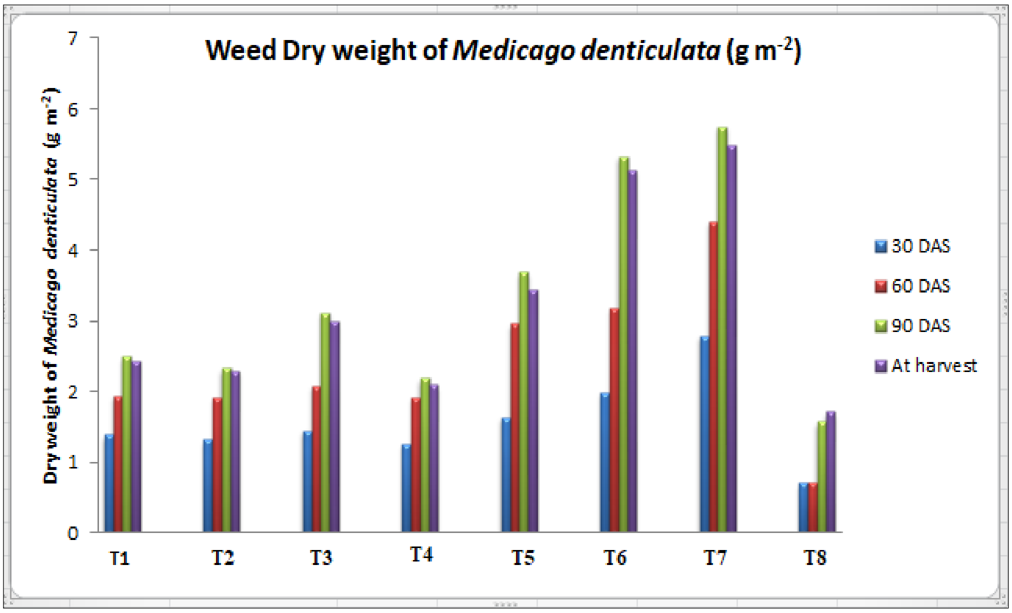

Fig. 10. Weed dry weight of *Medicago denticulata* (g m^{-2}).

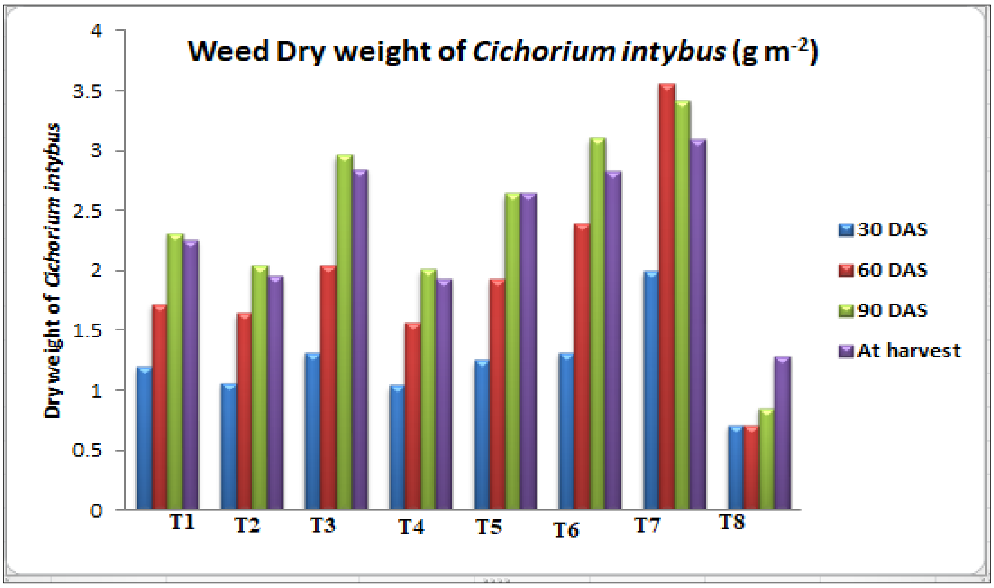

Fig. 11. Weed dry weight of *Cichorium intybus* (g m^{-2}).

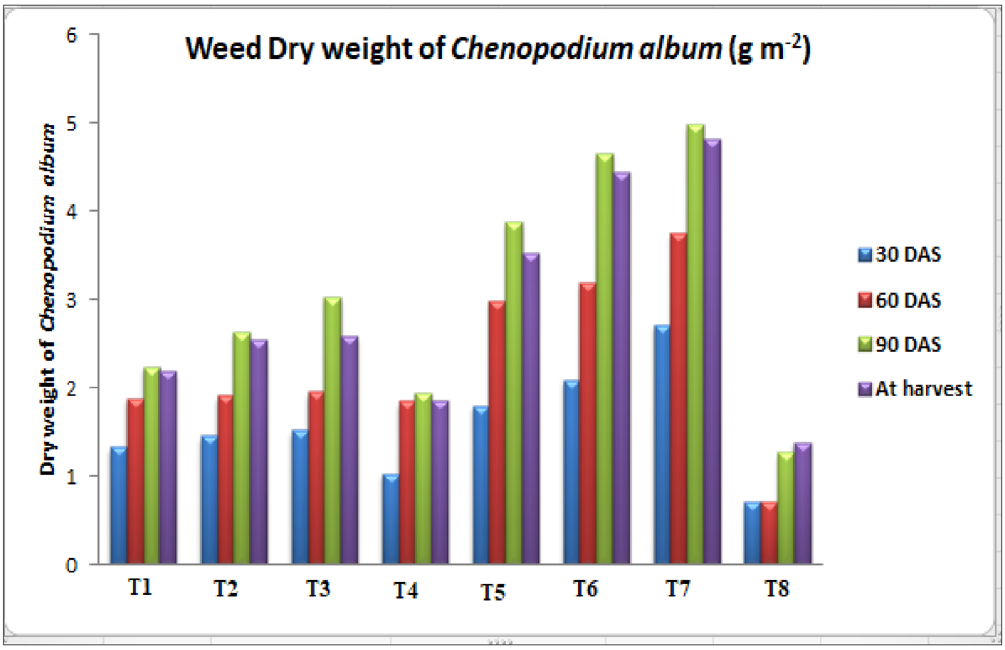

Fig. 12. Weed dry weight of *Chenopoium album* (g m^{-2}).

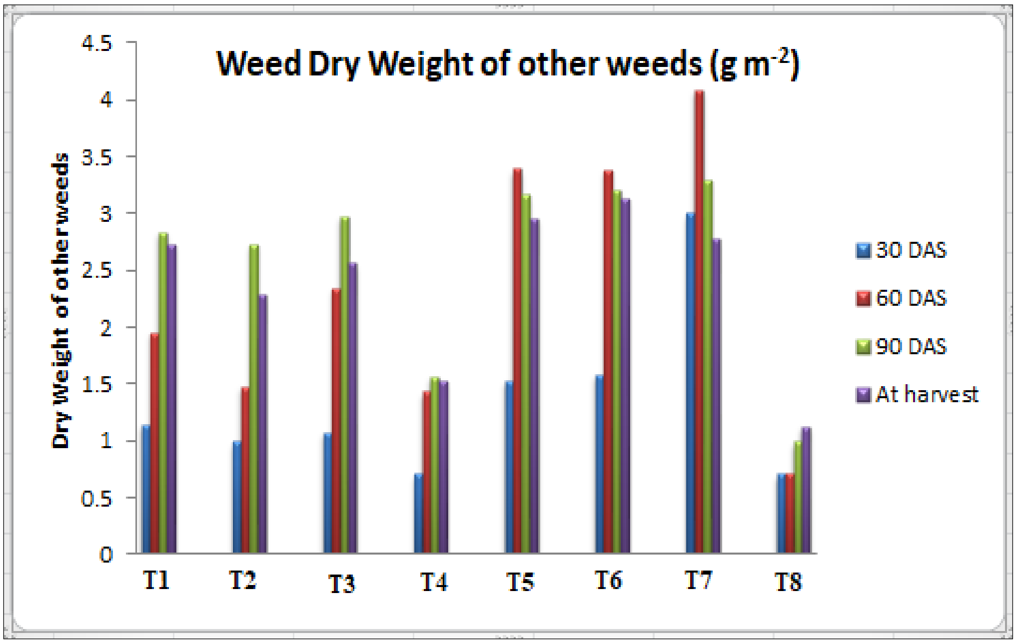

Fig. 13. Weed dry weight of other weeds (g m^{-2}).

matter under T8 was noted, possibly due to reduced interspecies competition and higher light penetration. Overall, T8 continued to record the lowest total and species-wise dry matter, followed by T4 and T3, while T7 showed the highest. T8, T4 and T3 effectively reduced grassy weed dry matter, whereas poor control was observed in T7 and T2. Among broad-leaved weeds, maximum control occurred under T8, followed by T4 and T2, with poor control in T7 and T6. *Medicago denticulata* and *Chenopodium album* maintained the highest dry matter accumulation at harvest, while other species showed a marked decline due to suppression by early -emerging weeds. Comparable findings were also documented by (28), (26) and (29), supporting the results of the present study. Earlier reports (29) indicated that the application of Pendimethalin as both a pre-emergence and post-emergence herbicide significantly reduced weed dry weight. Further, the effects of pre and post emergence herbicides on weeds in lentil crop. The results showed that the herbicidal treatments using pendimethalin (36). Imazethapyr and oxyfluorfen recorded lower weed dry weight. This is likely because grassy weeds are highly susceptible to herbicides such as Pendimethalin, Oxyfluorfen, Imazethapyr, while broad-leaved weeds are effectively controlled by Pendimethalin and sedge weeds by Imazethapyr. These findings suggested that the broad-spectrum activity of Pendimethalin, Oxyfluorfen and Imazethapyr effectively suppressed weed growth, resulting in lower weed biomass.

Weed control efficiency (WCE):

The WCE (%) at 30 days interval and at harvest stage as influenced by different treatments has been summarized and presented in Fig. 14. It was found that in all the treatments, the efficiency of weed control continued to show a declining trend throughout different time intervals of crop growth and this decline was greater under T6 followed by T5.

At 30 DAS, T8 recorded the highest WCE (100 %) followed by T4 (94.14 %) and T3 (86.26 %) and the least was recorded under T7. At 60 DAS, the highest WCE (100 %) was obtained under T8 followed by T4 (89.46 %) and T3 (82.86 %). The least WCE was obtained under T7. At 90 DAS, the highest WCE was recorded under T8 (95.36 %) which was followed by T4 (89.43 %) and T3 (72.15 %), whereas the least WCE was obtained under T7. Like all the previous observations, the highest WCE at harvest stage was obtained under T8 (90.74 %) followed by T4 (94.14 %) and T3 (86.26 %) and the least WCE was recorded under T7.

In comparison to the weedy check (T7), herbicidal spray decreased the dry mass of weeds and successfully killed weed seeds and weeds, which ultimately led to higher WCE. Similar results were also reported by (37-40, 32). The effects of various herbicides, including Imazethapyr, Pendimethalin, Quizalofop-p-ethyl and Chlorimuron-ethyl, on the growth, yield and economics of lentil was evaluated earlier (30). Their findings indicated that the highest weed control efficiency (58.83 %) and the lowest weed index (21.06 %) were achieved under specific herbicidal treatments. Similarly, Pendimethalin application resulted in the highest weed control efficiency (94.10 %) in lentil was reported earlier (3). The effective weed management observed in these studies was attributed to the broad-spectrum activity of the herbicides used.

Yield attributes and yield:

The yield attributes and yield of lentil as influenced by different treatments are given in Table 5. The significantly maximum number of pods plant^{-1} was produced under T8 and it was at par to T4, T3 and T1. The least number of pods plant^{-1} was obtained under T7. Number of seeds pod^{-1} and 100-seed weight were not affected significantly due to different treatments. However, the maximum number of seeds pod^{-1} and 100-seed weight were obtained under T8 and the least number of seeds pod^{-1} were under T7. Yield and harvest index were significantly maximum under T8, but it was at par with T4. The lowest seed yield, stover yield and harvest index was recorded under T7. The results of the present study are consistent with the observations reported by previous researchers (31, 37) and investigated the effects of post-emergence herbicides on the yield and economics of soybean (37). The study revealed that herbicides such as Imazethapyr, Quizalofop-p-ethyl, Chlorimuron-ethyl, Fenoxaprop and Quizalo significantly influenced seed yield and weed density. The highest seed yield (2251 kg/ha) was recorded in the weed-free check (hand weeding), followed by treatments with Imazethapyr, Quizalo and Fenoxaprop. The results indicated that the application of post-emergence herbicides effectively

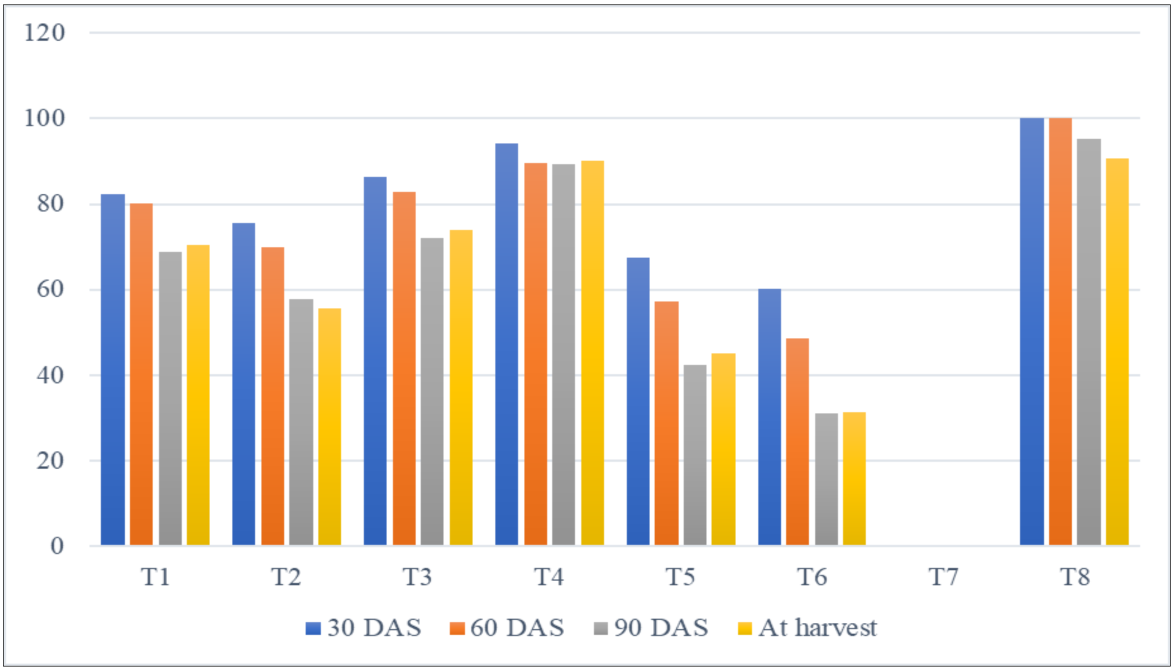

Fig. 14. Weed control efficiency (%) in lentil at different time intervals as influenced by weed management practices.

Table 5. Yield attributes and yield of lentil as influenced by weed management practices

Weed management practices	Pods plant^{-1} (No.)	Seeds pod^{-1} (No.)	100 seed weight (g)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Harvest index (%)
T1	32.23	1.43	3.15	794	1525	34.2
T2	28.53	1.30	3.19	783	1508	34.2
T3	31.80	1.40	3.18	840	1566	34.9
T4	32.47	1.50	3.20	888	1607	35.6
T5	25.20	1.43	3.11	707	1467	32.5
T6	25.03	1.47	3.17	678	1429	32.2
T7	21.00	1.27	2.95	517	1269	28.9
T8	36.67	1.57	3.22	979	1690	36.7
SEm ±	2.48	0.11	0.13	38	52	0.9
CD (p=0.05)	7.53	NS	NS	115	158	2.7

contributed to weed management and yield improvement in soybean. While the present study focuses on assessing the efficacy and economic viability of new-generation herbicides in lentil, previous reports emphasized the need to complement herbicide-based approaches with cultural and mechanical strategies to effectively manage herbicide-resistant weeds in lentil (41). Their integrated approach-combining higher seeding densities, mechanical weed control and reduced-rate non-ALS herbicides-achieved weed suppression and crop yields comparable to those obtained under full-rate herbicide applications, while minimizing dependence on single-mode-of-action chemicals. Incorporating such Integrated Weed Management (IWM) strategies into herbicide evaluation studies can enhance long-term sustainability, mitigate resistance development and promote ecologically balanced weed control systems.

Weed index

The data on WI have been summarized and presented in Fig. 15. The weed management practices had a remarkable influence on weed index. Maximum weed index was recorded under T7 (47.31 %). The minimum WI (9.19 %) among the herbicidal treatments was recorded under T4 followed by T3 (14.96 %). The maximum WI was recorded under the T7, where no weed management practices are adopted, which ultimately resulted in yield reduction. Similar observations were made earlier (26, 42). According to previous researchers (43), the post-emergence application of Imazethapyr at 50 g ha^{-1} at 20 DAS resulted in the maximum weed control efficiency and the minimum weed index (18.2 %) compared to other post-emergence herbicides such as Quizalofop-ethyl and Pendimethalin in field pea. The findings of former studies demonstrated that pre-emergence herbicides such as *prometryn*, when complemented with timely manual weeding, remain highly effective components of lentil weed management (44). Their observation that a single hand weeding can achieve yield levels comparable to certain chemical treatments highlighted the importance of integrating manual control methods into comparative studies and evaluating their cost-effectiveness under local labour and input conditions. The limited efficacy of the combined pre- and post-emergence herbicide application in their study was likely due to factors such as improper timing, rapid degradation of the pre-emergence residue, insufficient overlap in the weed control spectrum and potential chemical antagonism. Therefore, optimizing application timing, selecting compatible herbicide combinations and incorporating cultural practices are essential to maximize the effectiveness and sustainability of integrated weed management strategies.

Economics

Different parameters of economics like cost of cultivation, returns and benefits cost ratio were computed and shown in Table 6. The cost of cultivation (Rs 29781 ha^{-1}), gross returns (Rs 64805 ha^{-1}) and net returns (Rs 35024 ha^{-1}) were obtained highest in T8. Among the herbicidal treatments, T3 recorded the maximum cost of cultivation (Rs 26241 ha^{-1}), while, T4 recorded the maximum gross returns (Rs 58673 ha^{-1}) and net returns (Rs 35007 ha^{-1}). The minimum returns were observed in T7. The highest benefit cost ratio (2.48) was noticed in T4 followed by T2 (2.30). These results are consistent with the study findings of (37, 45). The effect of herbicides such as Pendimethalin and Quizalofop-p-ethyl on lentil crop was analysed earlier (45). The economic analysis revealed that the application of pre-emergence herbicide Pendimethalin and post-emergence

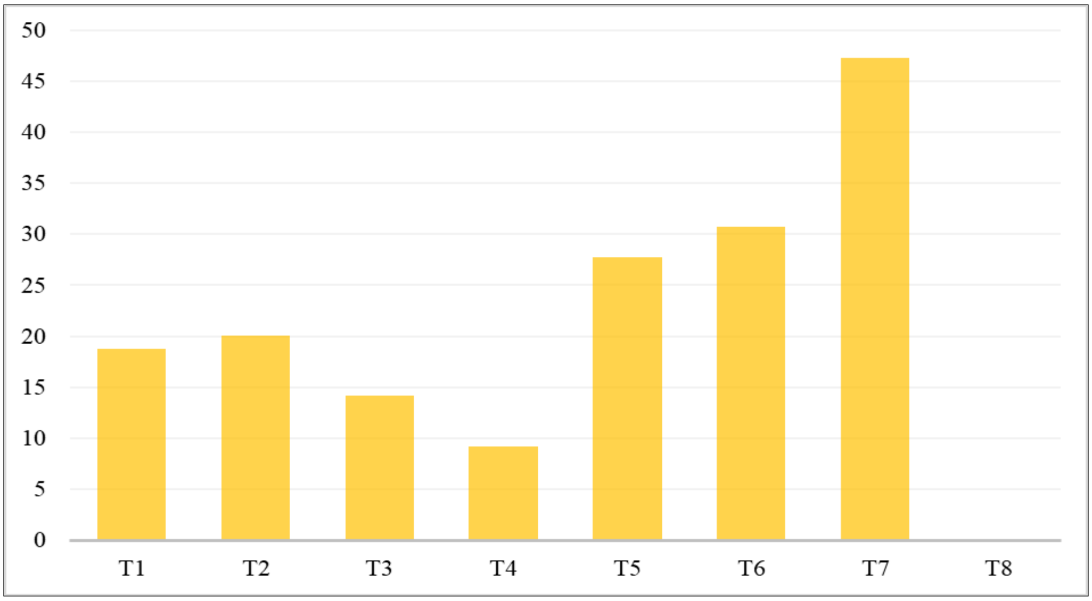

Fig. 15. Weed index (%) in lentil as influenced by weed management practices.

Table 6. Economics of lentil as influenced by weed management practices

Weed management practices	Total cost of cultivation (Rs ha^{-1})	Gross monetary returns (Rs ha^{-1})	Net monetary returns (Rs ha^{-1})	B:C ratio
T1	22991	52553	29562	2.29
T2	22561	51829	29268	2.30
T3	26241	55527	29286	2.12
T4	23666	58673	35007	2.48
T5	22561	46863	24302	2.08
T6	24981	45006	20025	1.80
T7	21031	34459	13428	1.64
T8	29781	64805	35024	2.18

herbicide Quizalofop-ethyl resulted in higher net returns (Rs. 17200/ ha and Rs.20400/ha, respectively) and benefit-cost ratios (1.92 and 2.04, respectively). This implied that use of chemical herbicides was effective weed management especially during manual labour scarcity.

Comparative insights on the use of botanicals and chemical herbicides for weed control in lentil

The use of synthetic herbicides has long been a predominant strategy in weed management owing to their rapid efficacy and ease of application. However, continuous reliance on chemical herbicides such as Pendimethalin, Imazethapyr and Quizalofop-ethyl has raised substantial ecological and agronomic concerns, including the development of herbicide-resistant weed biotypes, residual soil toxicity and adverse impacts on non-target organisms (46). Although these herbicides are effective in suppressing weed biomass, their repeated use often disrupts soil microbial activity and nutrient dynamics, thereby compromising soil fertility and biodiversity (47).

Conversely, botanical and microbial-based weed management approaches present sustainable and environmentally compatible alternatives. Botanicals such as *Parthenium hysterophorus*, *Eucalyptus globulus* and *Azadirachta indica* possess strong allelopathic potential, inhibiting weed seed germination and root elongation through the release of secondary metabolites, including phenolics and terpenoids was reported previously (48). Similarly, microbial bioherbicides derived from species such as *Phoma herbarum* and *Fusarium oxysporum* have demonstrated selective weed suppression without adversely affecting crop growth or soil microbiota (49). Apart form these, the application of indigenous formulations such as Panchagavya, composed of five cow-based products-cow dung, cow urine, milk, curd and ghee-has shown potential in effective weed management (50). Cow urine, a key constituent, contains phenolic compounds, ammonia and volatile fatty acids with allelopathic properties that inhibit weed seed germination and early seedling growth (51). In addition, foliar or soil application of Panchagavya promotes crop growth and canopy expansion, enhancing light interception and reducing the photosynthetically active radiation available to weeds. This combined biochemical and physiological suppression effectively reduces weed density and biomass (52). Hence, Panchagavya serves as both a biostimulant and bio-suppressant, improving crop vigor while minimizing weed pressure, making it a valuable component of eco-friendly and integrated weed management systems.

In addition to these strategies, the development of herbicide -tolerant crop varieties offers a promising solution to prevent crop injury and mortality caused by herbicide application. Various lentil accessions for tolerance to post-emergence herbicides, specifically Imazethapyr and Metribuzin was evaluated earlier (53). The findings revealed that herbicide application led to delayed flowering, reduced plant height and visible crop injury in susceptible genotypes. However, sixteen accessions were identified as herbicide-tolerant, exhibiting no adverse effects from the treatments.

While synthetic herbicides provide immediate and broad-spectrum weed control, their prolonged use has contributed to ecological imbalances, including weed flora shifts and chemical residues in the environment. In contrast, botanical, microbial and indigenous formulations, though slower in action, enhance long-term soil health, environmental safety and resistance management. Herbicide tolerant crops could also be one of the possible solutions. Therefore, integrating these approaches within an Integrated Weed Management (IWM) framework offers a balanced strategy-combining the effectiveness of chemical herbicides with the sustainability of biological alternatives.

Conclusion

Weed population was reduced significantly due to weed management practices either through the application of pre-emergence herbicides, post-emergence herbicides, hand weeding, or a combination of PE with POE. Out of which, combination of pre-emergence with post emergence herbicide showed remarkable results. The least density of total weeds was observed under T4 among the herbicidal treatments. The lowest WI and better weed control were observed under T8 followed by T4. The maximum gross returns (Rs 58673 ha^{-1}) and net returns (Rs 35007 ha^{-1}) were obtained under T4, along with maximum B: C ratio (2.48). From the research findings, it can be concluded that considering the current challenges of labour scarcity and rising labour costs in modern agriculture, an integrated approach combining chemical weed control using herbicides during the early stages of crop growth and mechanical weeding for managing late-emerging weeds offers an economical and efficient weed management strategy. The effectiveness of novel compounds as PE and POE, both alone and in combination, should be the main focus of future studies. There are also possibilities to test other lentil varieties with the same or different herbicide combinations under different edaphic conditions to have a comprehensive outcome. At the same time, through Integrated Weed Management approach more use of botanicals, microbial and indigenous formulations as well as herbicide tolerant crops should be emphasized for ecofriendly weed management.

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Authors' contributions

NA and KVP prepared the manuscript, and KK reviewed it for improvements. KVP, SD, SPR and LJ assisted in revising the manuscript based on the reviewers' comments. DKC and GKS supported the preparation of the manuscript in accordance with the journal guidelines. 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.

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