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Weed control, yield and profitability of peas as influenced by integrated chemical and mechanical methods

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Abstract

Pre- or post-emergence herbicides alone are insufficient to manage heavy infestation of diverse weed flora in peas. Integrated use of chemical weed control along with mechanical weeding could give better weed management. Therefore, this study aimed to evaluate the comparative effects of using post-emergence herbicides (flumetsulam and bentazone) or rotary weeding, either alone or in combination with pre-emergence herbicides (s-metolachlor and pendimethalin) on yield of peas. Results revealed that mechanical weed control with rotary weeder [15, 30 and 45 days after sowing (DAS)] was the most effective with the greatest reduction in total weed density and dry biomass (94-96%), and increase in pods plant^{-1}, fresh pod weight, fresh pod yield (144-185%), and benefit-cost ratio (1.88). Pre-emergence application of s-metolachlor and/or pendimethalin followed by post-emergence application of bentazone could be ranked second regarding weed control; however, pre-emergence application of pendimethalin + post-emergence application of bentazone gave better yield and profitability than pre-emergence application of s-metolachlor + post-emergence application of bentazone. A significant negative relationship of total weed dry biomass with fresh pod yield indicated that yield loss was associated with weed flora and could be reduced by better weed control. Conclusively, sole rotary weeding (15, 30 and 45 DAS) or integration of pre-emergence pendimethalin application with post-emergence bentazone application gave better weed control along with higher pod yield and profitability of peas.

Keywords: Benefit-cost ratio, Herbicides, Integrated weed management, *Pisum sativum*, Rotary weeding, Yield loss

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Introduction

Pea (*Pisum sativum* L.) is second largest pulse crop globally and is widely cultivated for its edible seed. Being leguminous crop, peas are an essential source of dietary protein, vitamins, mineral nutrients, polyphenols, fiber and various bioactive compounds which are essential for human health (Wu et al., 2023). It is also very beneficial for augmenting soil fertility because it converts atmospheric nitrogen (N) in plant useable form and adds it in the soil through its symbiotic relationship with N fixing bacteria in their root nodules (Rana et al., 2015; Dhillon et al., 2022). Nevertheless, the persistent challenge of weed competition causes substantial losses in pea yield (40-70%), and hampers its quality and profitability (Harker, 2001; Fernandez et al., 2012). Peas are infested by diverse broad and narrow leaved weeds which pose threat to its sustainable cultivation because this crop is weak competitor of weeds (Spies et al., 2011; Abdallah et al., 2021; Kovács et al., 2023). Moreover, the critical period of competition of peas with weeds is quite long ranging from 50 to 60 DAS requiring persistent weed control for longer period (Bhyan et al., 2004; Kumar et al., 2009).

In pea crop, weeds are more often controlled by manual hoeing or application of pre-emergence herbicide. But hoeing is laborious, time consuming and un-economical for weed control in peas. Pendimethalin, an inhibitor of cell division and microtubules, is a broad-spectrum herbicide, controls some broad leaf and grassy weeds (Vighi et al., 2017; Mahajan & Chauhan, 2024). It is predominantly used as pre-emergence herbicide to control weeds in peas, but its continuous use could cause shift in weed flora and herbicide resistance problems (Chen et al., 2021). S-metolachlor, a long chain fatty acid inhibitor, is used as pre-emergence herbicide in many crops including peas and controls small seeded broad leaf and grassy weeds (Rangani et al., 2021; Abdullah et al., 2025). Previous research has demonstrated that the efficacy of weed control in peas and other vegetables by pre-emergence herbicides was inferior when applied solely or even integrated with one hoeing or post-emergence herbicide (Eskin, 2000; Brijbhooshan & Shalini, 2017). Hence, the integrated use of pre- and post-emergence herbicides could provide better and persistent weed control (Kaur et al., 2020). Bentazone, a photosynthetic inhibitor, is post-emergence herbicide that controls the broad-leaved weeds and sedges in peas and many other crops (Ali et al., 2020; Abdallah et al., 2021). Similarly, flumetsulam, an acetolactate synthase (ALS) inhibitor is used as post-emergence herbicide to control broad leaf weeds in peas (Székács, 2021).

Although, integration of pre- and post-emergence herbicides could be beneficial but emerging scenario of sustainable agriculture demands an integrated approach that utilizes the positive aspects of manual, chemical and mechanical weed control methods in weed control (Harker & O'Donovan, 2013; Pannacci & Tei, 2014; Abdullah et al., 2025). Mechanical weed control involving different farm implements provides a mechanized way of eradicating the weeds thereby reducing the dependency on the chemicals for weed control (Hussain et al., 2018; Das et al., 2024). Although, this method eliminates the issues related to chemical herbicides, it could be laborious, damaging to crop plants, more weather and soil conditions dependent, and often requires multiple passes through the fields (Boyd & Brennan, 2006; Hussain et al., 2018).

Among various mechanical weed control methods, rotary weeding is an important weed control method. Rotary weeding employs the use of a rotary weeder with adjustable active tines for weed control in vegetables (Chandel et al., 2021; Zheng et al., 2025). The utilization of a rotary weeder offers a precise and eco-friendly alternative to chemical herbicides, promoting soil aeration and nutrient mineralization, minimizing environmental impact, and ultimately enhancing crop yield (Leblanc & Cloutier, 2001). Rotary weeder is effective against diverse weeds, but it often depends upon the frequency of weeding, type of weeds and weed growth stage (Boyd & Brennan, 2006). Previous research has shown that multiple passes or integration of rotary weeding with other mechanical methods had more positive effect on weed control and crop yield (Leblanc & Cloutier, 2011; Shirtliffe & Johnson, 2012; Chandel et al., 2015; Alba et al., 2020). Moreover, weeds in intra-row spaces of row crops are not controlled by rotary weeding which causes 18-76% yield reductions (Chandel et al., 2021). Therefore, integration of pre- and post-emergence herbicides along with rotary weeding could be utilized for efficient and environmentally safe weed control. In this perspective, study was carried out to investigate the integrated use of chemical and mechanical weed control methods in peas. It was hypothesized that the sole and integrated use of herbicides along with rotary weeding would differ in their weed control efficacy and yield of pea. The results of this study will give better option of integrated weed management to pea growers.

Materials and Methods

Study was executed at research area of Vegetables and Oilseeds Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad, Pakistan (31º23′54″N latitude 73º03′55″E longitude and 185 m above sea level) during 2019-20 and 2020-21. Experimental soil was loam with 0.88% organic matter, 1.90 dS/m electrical conductivity, 8.1 pH, 0.05% total N, 8.7 mg kg^{-1} available P and 190 mg kg^{-1} available K.

Treatments details

Treatments included rotary weeding, and pre- and post-emergence herbicides at specified rates (Table 1). Experimental treatments were arranged in randomized complete block design, and each treatment was repeated thrice. Net plot size was 6 m × 2.5 m. In weed free control plots, the weeds were completely removed, while in un-weeded control, weeds were allowed to grow throughout crop growing season. Major weed species present in the experimental field were wild spinach (*Rumex dentatus* L.), wild garden cress (*Cronopus didymus* L.), lamb's quarter (*Chenopodium album* L.), blue pimpernel (*Anagallis arvensis* L.), wild oats (*Avena fatua* L.) and canary grass (*Phalaris minor* L.). Rotary weeding was carried out using a rotary weeder having adjustable tines. Pre-emergence herbicides (s-metolachlor and pendimethalin) were applied just after sowing whereas post-emergence herbicides (flumetsulam and bentazone) 25 DAS. Herbicides were applied with knapsack sprayer having flat-fan nozzle using 300 L ha^{-1} water at a pressure of 207 kPa. Meteorological conditions prevailing during the crop growing season are given in Table 2.

Table 1 Treatment details of the experiment

Codes	Treatments	Description
T_1	Flumetsulam	Post-emergence application at 0.02 kg ha^{-1} a.i. 25 DAS (BBCH scale 15)
T_2	Bentazone	Post-emergence application at 1.20 kg ha^{-1} a.i. 25 DAS (BBCH scale 15)
T_3	S-metolachlor + bentazone	S-metolachlor pre-emergence application at 1.92 kg ha^{-1} a.i. + bentazone post-emergence application at 1.20 kg ha^{-1} a.i. 25 DAS (BBCH scale 15)
T_4	Pendimethalin + bentazone	Pendimethalin pre-emergence application at 1.24 kg ha^{-1} a.i. + bentazone post-emergence application at 1.20 kg ha^{-1} a.i. 25 DAS (BBCH scale 15)
T_5	Rotary weeding	Three rotary weedings at 15, 30 and 45 DAS (BBCH scale 11, 17, 51, respectively)
T_6	S-metolachlor + rotary weeding	S-metolachlor pre-emergence at 1.92 kg ha^{-1} a.i. and one pass of rotary weeding was carried out at 25 DAS (BBCH scale 15)
T_7	Pendimethalin + rotary weeding	Pendimethalin pre-emergence application at 1.24 kg ha^{-1} a.i. + one rotary weeding at 25 DAS (BBCH scale 15)
T_8	Weed free control	Weeds were removed by hoeing, hand weeding and earthing-up throughout growing season
T_9	Un-weeded control	Weeds allowed to grow throughout growing season

Table 2 Meteorological conditions during pea growing seasons (2019-20 and 2020-21)

Month	Temperature (°C)						Total rainfall (mm)		Relative humidity (%)	
	Monthly maximum		Monthly minimum		Daily mean					
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
October	32.9	35.0	18.9	17.0	25.9	26.0	22.4	0.0	64.6	51.9
November	26.3	26.3	12.8	10.2	19.6	18.3	3.0	0.8	69.1	67.5
December	17.0	21.0	6.0	6.5	11.5	13.8	7.0	2.3	77.0	72.2
January	17.3	17.3	5.5	5.5	11.4	11.4	50.8	56.5	74.3	77.0
February	23.8	25.9	8.7	9.8	16.3	17.9	24.8	0.0	64.9	66.9
March	24.5	30.9	13.9	15.3	19.2	23.1	135.0	37.8	73.7	58.0
April	33.1	34.5	18.8	18.4	26.0	26.5	20.4	15.4	60.7	42.8
May	37.5	38.6	23.1	24.0	30.3	31.3	19.9	11.2	45.0	45.3

Source: Plant Physiology Section, Agronomic Research Institute, Ayub Agricultural Research Institute, Faisalabad

Crop husbandry

Pea variety Peas-2009 was sown on 10th and 12th October during 2019-20 and 2020-21 growing seasons, respectively. During both growing seasons, sowing was performed on margins of 125 cm wide beds made over well-pulverized and leveled soil and 10 cm plant to plant distance with seed rate of 75 kg ha^{-1}. Prior to sowing, seed was inoculated with *Rhizobium* bacterial culture obtained from Ayub Agricultural Research Institute (AARI), Faisalabad to enhance the nodulation. Fertilizers were applied at 88, 88 and 62 kg/ha N, P and K from urea, diammonium phosphate (DAP) and sulfate of potash (SOP) sources, respectively. The basal fertilizers included whole of DAP and SOP whereas bifurcated application of N was made at sowing and flowering stage. Irrigation (8-10 times) was applied according to soil and weather conditions, and crop needs during both growing seasons. Emamectin benzoate (1.9% EC) was applied at 9.5 g a.i. ha^{-1} to control pod borer by following the expert recommendations. Fresh green pods were harvested manually in three pickings when the pods were filled with seeds. The pickings started 70-75 DAS, and remaining pickings were performed with 15 days intervals during 2019-20 and 2020-21.

Weed control attributes

Total weed density (weed plants m^{-2}) was determined from each plot at 50 DAS. All types of weeds were counted collectively, then collected and dried in drying oven at 70 ± 5ºC until constant weight for determining the total weed dry biomass and expressed as g m^{-2}. Weed control efficacy, the percent decrease in total weed density by a weed control treatment in comparison to un-weeded control, was computed according to Kaur et al. (2020):

$$\text{Weed control efficacy (\%)} = \left[\frac{(\text{WP}_\text{c} - \text{WP}_\text{t})}{\text{WP}_\text{c}} \times 100\right]$$

where, WP_c and WP_t denote the total weed density (plants m^{-2}) of un-weeded control and respective treatment plots, respectively.

Weed control index was determined as the percent decrease in total weed dry biomass by a weed control treatment in comparison to weed free control, and was computed according to Kaur et al. (2020):

$$\text{Weed control index (\%)} = \left[\frac{(\text{WD}_\text{c} - \text{WD}_\text{t})}{\text{WD}_\text{c}} \times 100\right]$$

Where, WD_c and WD_t denotes the total weed dry biomass of weed free control and respective treatment plots, respectively.

Yield and related attributes of peas

At harvesting, the pods from randomly tagged five plants from each plot were counted to determine the number of pods $plant^{-1}$ and averaged. Fresh pod weight was determined by weighing ten collected fresh pods from tagged plants by an electric weighing balance and averaged. Seeds from collected pods were counted to determine the number of seeds pod^{-1} and averaged. Then, 100-seed weight was determined by counting the 100-seeds from each sample and weighing with an electric weighing balance. Fresh pod yield was determined by harvesting the plots manually in three pickings and summing the pod yield from all pickings and expressed as t ha^{-1}. Yield loss as compared to weed-free control was determined by using the formula of Dodamani & Das (2013):

$$Yield\ loss\ (\%) = \left[\frac{(Y_{wf} - Y_t)}{Y_{wf}} \times 100\right]$$

Where Y_{wf} and Y_t denote the fresh pod yield of weed free control and respective treatment plots, respectively.

Economic analysis

Calculation of the net returns, total cost and benefit-cost ratio (BCR) were performed as described by CIMMYT (1988). Fixed and variable costs were estimated by using the market prices of the land-preparation, used inputs (seed, irrigation, fertilizers, herbicides, insecticides, fungicides), labor and harvesting charges etc. Total cost was determined by summing the fixed and variable costs. Gross income was computed by multiplication of fresh pod yield with fresh pods market price. Total cost was subtracted from the gross income to find out the net returns. The BCR was figured out as follows:

$$\text{BCR} = \left[\frac{\text{Gross income}}{\text{Total cost}}\right]$$

Statistical analysis

The data related to weeds and pea crop was square root transformed before carrying out further statistical analyses. However, no difference was found in significance test between non-transformed and transformed data; hence, non-transformed original data of weeds as well as pea crop was used for further analyses. Significant difference between years (year effect) was found according to paired T-test. Therefore, data were separately analyzed and presented year wise. The analysis for significance of treatments was performed using one-way analysis of variance (Steel et al., 1997) using SPSS 21 software. Least significant difference was used for post-hoc test using 5% probability. The relationship of total weed density and dry biomass with fresh pod yield and weed control efficacy and index with yield loss was determined by using linear regression analyses.

Results

Total weed density and dry biomass

All weed control treatments significantly reduced the total weed density and dry biomass (Table 3). During both the years, sole application of mechanical weed control through three rotary weedings (15, 30 and 45 DAS) provided the better weed control resulting in 96% reduction in total weed density and 94-96% reduction in total weed dry biomass (Table 3). This treatment was followed by pre-emergence s-metolachlor application + post-emergence bentazone application as it reduced total weed density up to 84% and total weed dry biomass up to 91% than un-weeded control (Table 3). However, least weed control was given by sole application of post-emergence herbicides, flumetsulam and bentazone, as exhibited by reduction in total weed density (21-27 and 55-62%) and dry biomass (16-19 and 52-57%), respectively (Table 3).

Table 3 Influence of integrated weed control on total weed density and dry biomass

Treatments	Total weed density (plants m^{-2})		Total weed dry biomass (gm^{-2})	
	2019-20	2020-21	2019-20	2020-21
Flumetsulam	264.7±4.48 b	221.0±6.00 b	30.47±1.01 b	27.18±0.77 b
Bentazone	160.0±3.51 c	130.0±3.46 c	16.17±0.49 c	12.78±0.66 c
S-metolachlor + bentazone	55.0±1.53 g	49.0±1.04 g	4.33±0.39 g	3.01±0.30 g
Pendimethalin + bentazone	74.0±2.00 f	60.0±1.73 f	6.63±0.72 f	5.35±0.49 f
Rotary weeding	15.0±1.53 h	11.0±0.83 h	2.03±0.23 h	1.33±0.14 h
S-metolachlor + rotary weeding	90.0±2.08 e	81.0±2.08 e	10.20±0.61 e	8.45±0.79 e
Pendimethalin + rotary weeding	119.0±1.58 d	101.0±2.52 d	14.07±0.54 d	11.24±0.45 d
Weed free control	0.0±0.00 i	0.0±0.00 i	0.00±0.00 i	0.00±0.00 i
Un-weeded control	335.0±8.19 a	302.0±6.66 a	36.23±0.73 a	33.43±1.09 a

Values are mean ± SE. Within a column, means with different letters are significantly different at $P < 0.05$.

Weed control efficacy and index

Weed control efficacy and weed control index were significantly affected by different weed control treatments during both the years (Fig. 1 and 2). During first and second growing seasons, the weed control efficacy and weed control index were the highest (95-96% and 94-96%), respectively, for sole application of three rotary weedings (15, 30 and 45 DAS) (Fig. 1 & 2). Nonetheless, the efficacy of pre-emergence herbicides + rotary weeding was low as compared to sole rotary weeding (Fig. 1 & 2). The pre-emergence herbicides integrated with post-emergence application of bentazone had higher weed control efficacy although less than sole rotary weeding. The pre-emergence application of s-metolachlor + post-emergence application of bentazone was the second highest after sole rotary weedings as exhibited by their higher weed control efficacy (84%) and weed control index (88-91%), however, the weed control efficacy for pre-emergence application of pendimethalin + post-emergence application of bentazone was statistically similar during 2020-21 (Fig. 1 and 2). On the contrary, sole post-emergence herbicides, flumetsulam and bentazone, showed lowest weed control efficacy (21-27 and 16-19%) and weed control index (52-57 and 55-62%), respectively, during 2019-20 and 2020-21 (Fig. 1 and 2).

Fresh pod yield and related attributes of peas

Compared to untreated weedy check, all weed control treatments significantly enhanced the pod yield and yield related traits of peas, while reduced yield loss during both growing seasons (Tables 4 and 5; Fig. 3 and 4). Among all, sole application of mechanical weed control through three rotary weedings (15, 30 and 45 DAS) resulted in the highest increase in number of pods $plant^{-1}$, seeds pod^{-1}, 100-seed weight, fresh pod weight, and fresh pod yield (144-185%), and least yield loss (9-10%) respectively during 2019-20 and 2020-21 (Tables 4 and 5; Fig. 3 and 4). Pre-emergence application of pendimethalin + post-emergence application of bentazone followed this treatment regarding its pod yield and yield related attributes enhancing performance and decreasing the yield loss (Tables 4 and 5; Fig. 3 and 4). Pre-emergence application of pendimethalin + application of post-emergence bentazone caused more increase in fresh pod yield and yield related attributes than pre-emergence s-metolachlor application + post-emergence bentazone application (Tables 4 and 5; Fig. 3). While post-emergence herbicides flumetsulam and bentazone showed the least improvement performance regarding fresh pod yield (41-100%) and yield related traits, and decrease in yield loss (36-48%) of peas in comparison to other weed control treatments (Tables 4 and 5; Fig. 3 and 4). A significant negative linear relationship of fresh pod yield existed with total weed density (R^2 0.9156 and 0.8915) and dry biomass (R^2 0.8785 and 0.8372) during 2019-20 and 2020-21 (Fig. 5). Similarly, significant negative linear relationship of yield loss was observed with weed control efficacy (R^2 0.9157 and 0.8930) and weed control index (R^2 0.8628 and 0.8387) during 2019-20 and 2020-21 (Fig. 6).

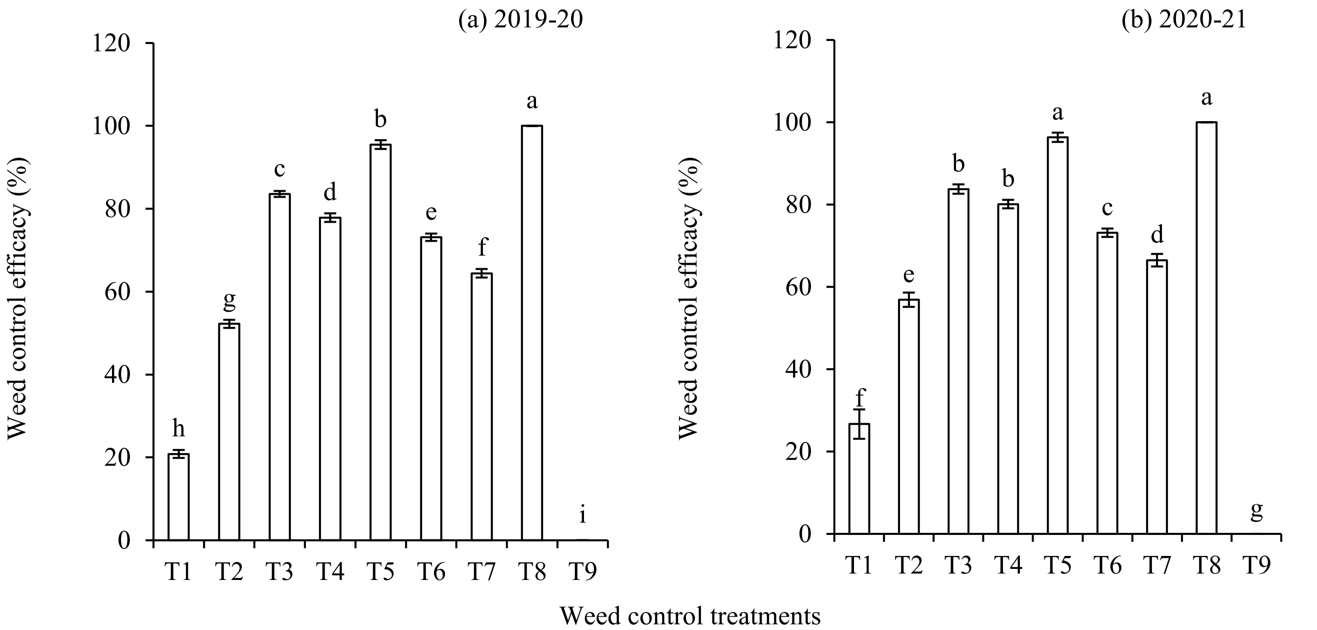

Fig. 1 Influence of integrated weed control on weed control efficacy (%) (a) 2019-20 (b) 2020-21 in green peas. Bars are mean ± SE. Bars with different letters differ significantly at $P < 0.05$. T_1: Flumetsulam, T_2: Bentazone, T_3: S-metolachlor + bentazone, T_4: Pendimethalin + bentazone, T_5: Rotary weeding, T_6: S-metolachlor + rotary weeding, T_7: Pendimethalin + rotary weeding, T_8: Weed free control, T_9: Un-weeded control

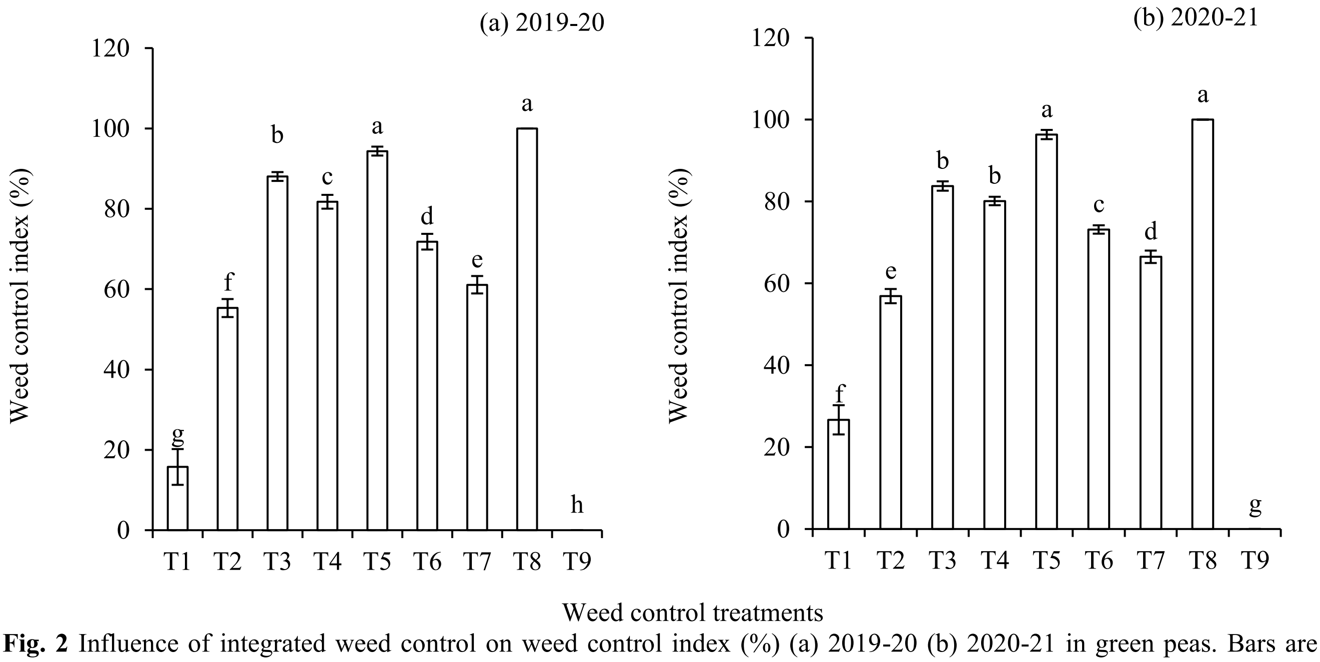

Fig. 2 Influence of integrated weed control on weed control index (%) (a) 2019-20 (b) 2020-21 in green peas. Bars are mean ± SE. Bars with different letters differ significantly at $P < 0.05$. T_1: Flumetsulam, T_2: Bentazone, T_3: S-metolachlor + bentazone, T_4: Pendimethalin + bentazone, T_5: Rotary weeding, T_6: S-metolachlor + rotary weeding, T_7: Pendimethalin + rotary weeding, T_8: Weed free control, T_9: Un-weeded control

Table 4 Influence of integrated weed control on number of pods $plant^{-1}$ and number of seeds pod^{-1} of the green peas

Treatments	No. of pods $plant^{-1}$		No. of seeds pod^{-1}	
	2019-20	2020-21	2019-20	2020-21
Flumetsulam	13.89±0.23 e	14.18±0.38 f	4.29±0.06 f	4.65±0.29 e
Bentazone	15.10±0.85 e	16.70±0.36 e	5.08±0.13 e	5.30±0.09 d
S-metolachlor + bentazone	17.80±0.30 cd	19.03±0.36 d	5.80±0.06 d	7.00±0.21 b
Pendimethalin + bentazone	19.93±0.32 b	23.25±0.37 b	7.32±0.07 c	7.41±0.21 b
Rotary weeding	22.24±0.48 a	24.10±0.26 b	8.10±0.15 b	8.18±0.09 a
S-metolachlor + rotary weeding	17.25±0.22 d	18.69±0.51 d	5.66±0.08 d	6.16±0.10 c
Pendimethalin + rotary weeding	19.10±0.24 bc	21.00±0.31 c	7.20±0.06 c	7.16±0.21 b
Weed free control	23.47±0.69 a	25.21±0.38 a	8.41±0.05 a	8.22±0.18 a
Un-weeded control	11.66±0.12 f	12.98±0.33 g	2.30±0.06 g	3.15±0.14 f

Values are mean ± SE. Within a column, the means with different letters are significantly different at $P < 0.05$.

Table 5 Influence of integrated weed control on 100-seed weight and fresh pod weight of green peas

Treatments	100-seed weight (g)		Fresh pod weight (g)	
	2019-20	2020-21	2019-20	2020-21
Flumetsulam	42.40±0.61 d	43.88±0.41 f	5.30±0.06 e	4.90±0.18 e
Bentazone	44.13±0.69 cd	45.16±0.54 ef	6.00±0.24 cd	5.38±0.22 de
S-metolachlor + bentazone	45.77±0.52 c	46.29±0.49 de	5.97±0.29 cde	6.60±0.17 bc
Pendimethalin + bentazone	48.27±0.13 b	49.74±0.75 bc	6.60±0.35 bc	7.30±0.25 b
Rotary weeding	49.93±0.64 ab	50.42±0.66 ab	7.20±0.30 ab	8.30±0.25 a
S-metolachlor + rotary weeding	45.43±0.39 c	46.92±0.22 d	5.80±0.19 de	6.20±0.20 cd
Pendimethalin + rotary weeding	48.20±0.47 b	48.69±0.72 c	6.80±0.20 b	6.60±0.18 bc
Weed free control	50.50±0.67 a	51.73±0.33 a	7.50±0.23 a	8.60±0.26 a
Un-weeded control	38.90±0.84 e	40.26±0.43 g	3.60±0.28 f	3.80±0.56 f

Values are mean ± SE. Within a column, the means with different letters are significantly different at $P < 0.05$.

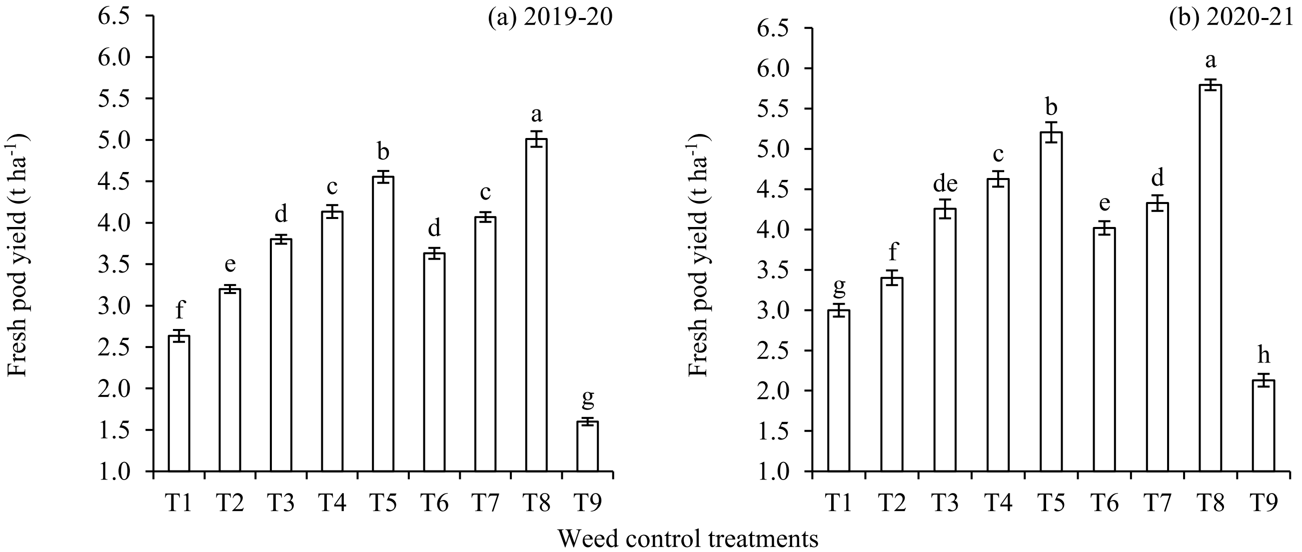

Fig. 3 Influence of integrated weed control on fresh pod yield (t ha^{-1}) (a) 2019-20 (b) 2020-21 of green peas. Bars are mean ± SE. Bars with different letters differ significantly at $P < 0.05$. T_1: Flumetsulam, T_2: Bentazone, T_3: S-metolachlor + bentazone, T_4: Pendimethalin + bentazone, T_5: Rotary weeding, T_6: S-metolachlor + rotary weeding, T_7: Pendimethalin + rotary weeding, T_8: Weed free control, T_9: Un-weeded control

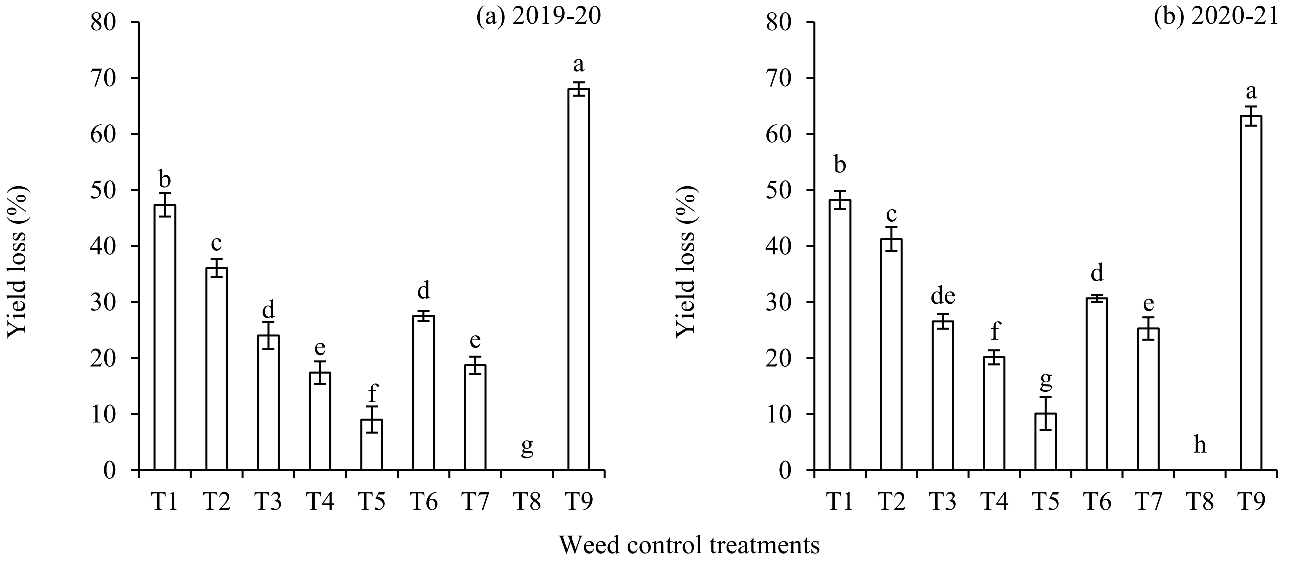

Fig. 4 Influence of integrated weed control on yield loss (%) (a) 2019-20 (b) 2020-21 of green peas. Bars are mean ± SE. Bars with different letters differ significantly at P < 0.05. T_1: Flumetsulam, T_2: Bentazone, T_3: S-metolachlor + bentazone, T_4: Pendimethalin + bentazone, T_5: Rotary weeding, T_6: S-metolachlor + rotary weeding, T_7: Pendimethalin + rotary weeding, T_8: Weed free control, T_9: Un-weeded control

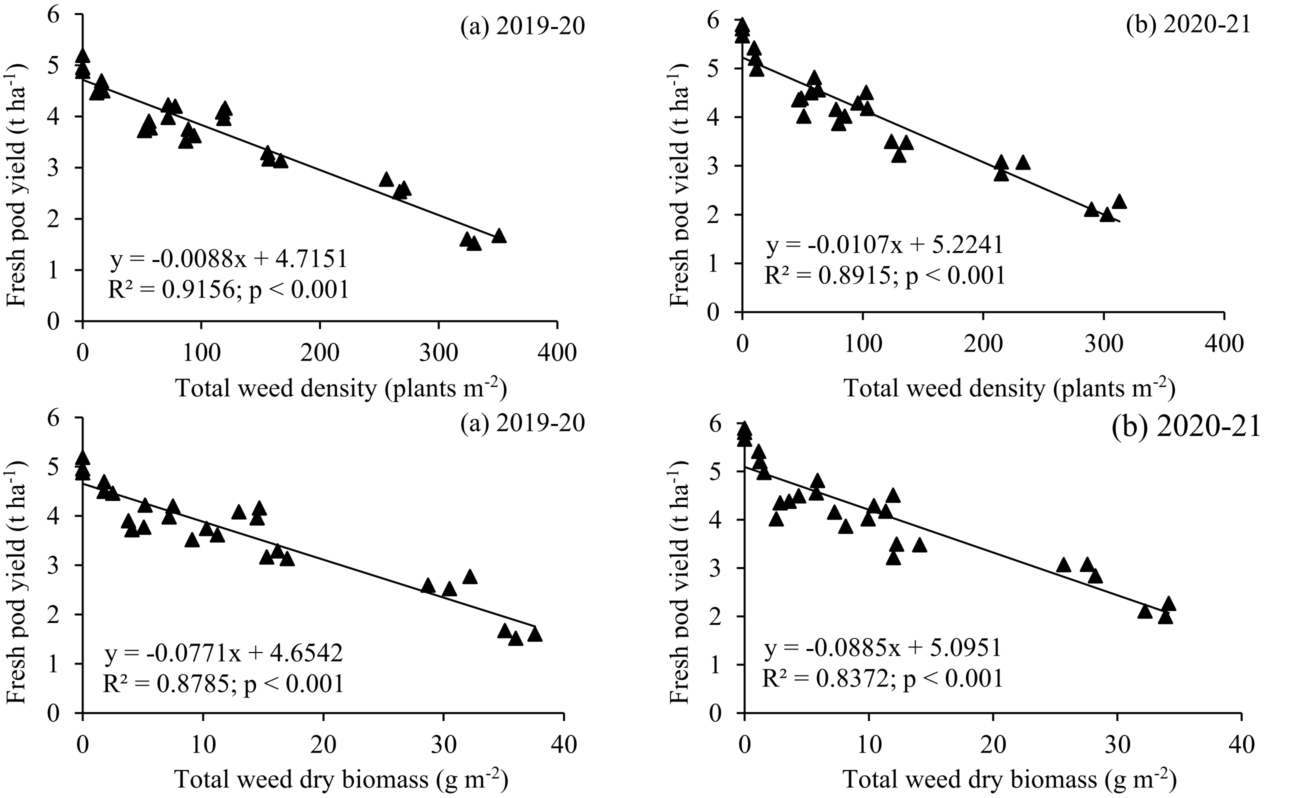

Fig. 5 Relationship between (a,b) total weed density (plants m^{-2}) and fresh pod yield (t ha^{-1}), and (c,d) total weed dry biomass (g m^{-2}) and fresh pod yield (t ha^{-1}). Coefficients of determination (R^2), significance of coefficients (P < 0.05) and dependence of fresh pod yield (y) on (a) total weed density (x) and (b) total weed dry biomass (x) are given

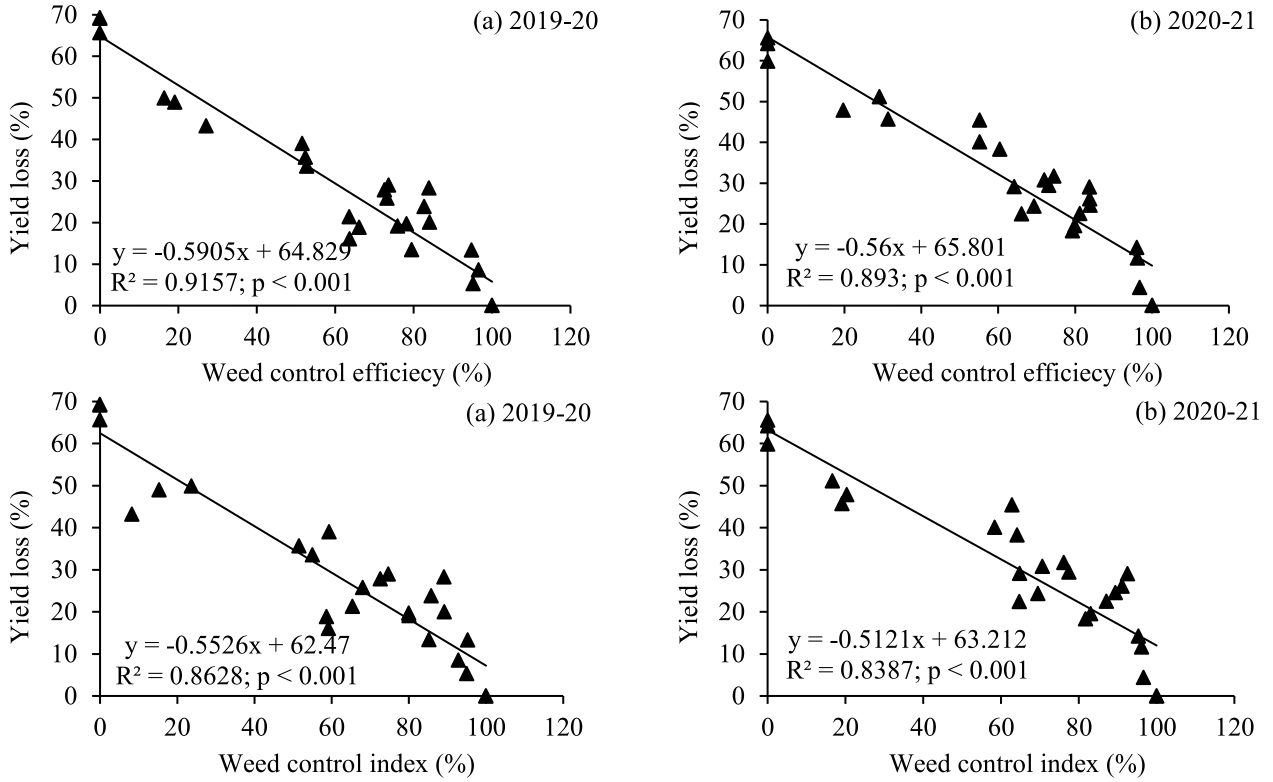

Fig. 6 Relationship between (a,b) weed control efficacy (%) and yield loss (%), and (c,d) weed control index (%) and yield loss (%). Coefficients of determination (R^2), significance of coefficients ($P < 0.05$) and dependence of yield loss (%) on (a) weed control efficacy (x) and (b) weed control index (x) are given.

Economic analysis

Economic analysis revealed that among weed control treatments, three rotary weedings (15, 30 and 45 DAS) attained the highest BCR (1.88) (Table 6). This treatment was followed by pre-emergence pendimethalin application + post-emergence bentazone application by gaining the second highest BCR (1.63). It was also revealed that the highest cost was exhibited by pre-emergence pendimethalin application + post-emergence bentazone, even more than weed free control, while minimum cost was recorded by pre-emergence application of s-metolachlor + rotary weeding (25 DAS) (Table 6).

Table 6 Comparison of benefit-cost ratio of weed control treatments

Treatments	AGY (kg ha^{-1})	GI (Rs. ha^{-1})	Fixed cost (Rs. ha^{-1})	VC (Rs. ha^{-1})	Total cost (Rs. ha^{-1})	Net benefits (Rs. ha^{-1})	BCR
Flumetsulam	2535	126720	111709	2500	114209	12511	1.11
Bentazone	2971	148523	111709	4750	116459	32064	1.28
S-metolachlor + bentazone	3628	181373	111709	6750	118459	62914	1.53
Pendimethalin + bentazone	3943	197145	111709	9438	121147	75998	1.63
Rotary weeding	4392	219555	111709	5000	116709	102846	1.88
S-metolachlor + rotary weeding	3442	172103	111709	2000	113709	58394	1.51
Pendimethalin + rotary weeding	3778	188910	111709	4688	116397	72513	1.62
Weed free control	4892	243090	111709	7908	119617	123474	2.03
Un-weeded control	1679	83925	111709	0	111709	-27784	0.75

AGY = Adjusted grain yield (kg ha^{-1}); GI = Gross income (Rs. ha^{-1}); VC = Variable cost (Rs. ha^{-1}); BCR = Benefit cost ratio; Average adjusted fresh pod yield = 10% less than actual fresh pod yield averaged over two years (2019-20 and 2020-21); Cost and income was estimated by using the prevailing market prices for inputs and fresh green pea pods, respectively, in Pakistan and averaged over two years (2019-20 and 2020-21).

Discussion

Compared to weedy check, all weed control treatments reduced weed infestation and improved peas yield but three rotary weedings (15, 30 and 45 DAS) alone was the most effective and economical even than the integrated use of pre-emergence herbicides + one rotary weeding with highest weed control efficacy (95-96%), reduced total weed density (96%) and dry biomass (94-96%), and increased pea yield (144-185%) (Table 3; Fig. 1 & 3). This indicated that repeated mechanical operations are required for effective weed control and yield increase even if integrated with pre-emergence herbicides or other weed control methods (Kolb et al., 2012; Pannacci & Tei, 2014; Pannacci et al., 2018). Because the rotary weeder had adjustable tines therefore least crop injury occurred due to which yield benefits were not out weighted, even at later growth stage (45 DAS) (Zheng et al., 2025). Similar to our results, previous research has reported that effective weed control and yield increase was possible with multiple passes of rotary weeder (Leblanc et al., 2006; Pannacci et al., 2018; Alba et al., 2020). Although, pre-emergence herbicides gave better weed control but integration of one-time rotary weeding (25 DAS) was not enough for weed control after stand establishment as critical weed-crop competition period (up to 60 DAS) surpassed the weed control thereby reducing the effectiveness of weed control (Bhyan et al., 2004; Abdallah et al., 2021).

Integrated use of pre- and post-emergence herbicides are the best alternative of intensive mechanical weed control as it effectively controlled the weeds (Table 3) and improved yield as compared to un-weeded control (Fig. 3). Previous research has reported similar results regarding better weed control and yield of peas and other crops by the integrated use of pre-and post-emergence herbicides (Shalini & Singh, 2014; Hajebi et al., 2016; Delchev et al., 2018; Kaur et al., 2020; Abdullah et al., 2025). In preset study, pea yield resulted from integrated use of pre- and post-emergence herbicides was lower than sole rotary weeding (Fig. 3) which could be attributed to less effective weed control by herbicides than rotary weeding as manifested by higher total weed density and dry biomass (Table 3). In present study, the pre-emergence s-metolachlor application + post-emergence bentazone application was more effective regarding weed control but exhibited lower pea yield than pre-emergence pendimethalin application + post-emergence bentazone application (Table 3; Fig. 3). This could be attributed to the more toxic effect of s-metolachlor on emergence and early growth of weeds as well as pea crop than pendimethalin (Stephenson et al., 2013) which is also evident from the results of treatments including pre-emergence application of s-metolachlor and pendimethalin followed by rotary weeding (Table 3 & 4; Fig. 3).

Sole application of post-emergence herbicides gave the lowest weed control efficacy and least pea yield among all weed control treatments (Fig. 1 & 3). Sole application of flumetsulam remained least effective regarding weed control showing least reduction in total weed density (21-27%) and dry biomass (16-19%) from un-weeded control (Table 3). This could be explained by the fact that flumetsulam controls only broad leaf weeds due to which narrow leaved weeds remained unharmed (Székács, 2021) resulting in lowest weed control efficacy and index, and ultimately less pea yield (Fig. 1-6). On the contrary, better weed control efficacy and pea yield was provided by bentazone (52-57 and 60-100%) than flumetsulam (21-27 and 41-65%), (Fig. 1 & 5) because it is broad-spectrum herbicide and kills the broad leaf weeds as well as narrow leaves weeds (Ali et al., 2020). Previous research has shown that bentazone was superior to other post-emergence herbicides because it is a highly selective broad-spectrum herbicide for pea crop (Delchev et al., 2018; Abdallah et al., 2021). Furthermore, least weed control efficacy of solely applied post-emergence herbicides indicates that more applications of post-emergence herbicides are needed for weed control during the critical weed-crop competition period of pea.

The weed control treatments significantly improved the pea yield by reducing the total weed density and dry biomass and the results were consistent across the years (Table 3; Fig. 3). Reduced weed competition with pea crop resulted in enhanced number of pods plant^{-1}, seeds pod^{-1} and fresh pod weight which ultimately enhanced the fresh pod yield of pea crop (Tables 4 and 5; Fig. 3). Moreover, yield loss was related to weed control efficacy and index which indicated that less weed interference due to efficient weed control could significantly improve the pea crop yield (Table 3; Fig. 5 & 6). Less weed interference and competition with crop plants results in improved leaf area and photosynthetic activity of plants leading to enhanced dry matter production and yield (Singh & Tripathi, 2004; Bhullar et al., 2015; Kaur et al., 2020; Akhtar et al., 2025). Previous studies have also reported similar results showing the increase in crop yield and decrease in yield loss with increase in weed control efficacy (Das, 2016; Kaur et al., 2020).

Economic analysis revealed that the economic returns and BCR were increased by better weed control (Table 6). However, except weed free control, the highest gross income and BCR were produced by sole rotary weeding three times (15, 30 and 45 DAS) and it was followed by pre-emergence application of pendimethalin + post-emergence application of bentazone (Table 6). This is attributed to higher fresh pod yield and lower cost of production in case of rotary weeding. However, pre-emergence application of pendimethalin + post-emergence application of bentazone had higher cost of production but produced higher crop yield and hence higher economic benefits (Table 6; Fig. 3). Previous studies have also reported similar results regarding economic returns and profitability by better weed control (Singh et al., 2011; Hajebi et al., 2016; Kaur et al., 2020).

Conclusion

Sole rotary weeding and/or pre-emergence pendimethalin application + post-emergence bentazone application caused maximum decrease in total weed density and dry biomass while exhibited the most pronounced weed control efficacy, fresh pod yield and BCR after weed free control. Hence, sole rotary weeding or integration of pre-emergence pendimethalin application with post-emergence bentazone application resulted in better weed control and fresh pod yield and could be employed for higher profitability of peas.

Authors contribution: Naveed Akhtar: Supervised the experiment. Ali Zohaib: Carried out statistical data analysis, economic analysis, paper write-up, and did overall management. Tahira Tabassum: Carried out data management and presentation. Babar Hussain Babar: Carried out field management and data curation. Muhammad Nawaz: Helped in data curation. Hafiz Naveed Ramzan and Muhammad Iqbal: Helped in review of literature. Saba Iqbal and Muhammad Faisal Shafiq: Helped in statistical analysis. Muhammad Tahir Latif: Helped in economic analysis. Mohsin Nawaz: Helped in revision and improvement of manuscript.

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