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EVALUATION OF WEED MANAGEMENT PRACTICES FOR IMPROVING GROWTH, YIELD AND ECONOMIC RETURNS IN GARLIC

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ABSTRACT

To evaluate the effects of crop residue mulch, cultural practices, and herbicide application on plant growth, yield, yield-attributing traits and economics of garlic, a field experiment was carried out during *rabi* season of 2022–23 at the Research Farm, Department of Vegetable Science, CCS Haryana Agricultural University, Hisar. The study consisted of fifteen treatments arranged in a Randomized Block Design with three replications. The results of the study revealed that manual hoeing at 30, 60, and 90 days after planting (T_{14}) proved to be most effective, recording the highest plant height at 60, 90, and 120 DAP (47.37, 60.62, and 78.95 cm, respectively), along with the highest number of leaves (10.13/plant) and found statistically comparable to the treatment pendimethalin 30% EC at 1000 g ha^{-1} applied as a pre-emergence followed by two hand hoeings at 30 and 60 DAP (T_3), where both treatments significantly outperformed the untreated control. The T_{14} also recorded superior results in yield-related parameters, including polar diameter (4.64 cm), equatorial diameter (4.88 cm), neck thickness (8.73 mm), number of cloves per bulb (31.21), clove length (2.91 cm), bulb weight (34.90 g), bulb yield (127.45 q ha^{-1}), total plant biomass (152.79 q ha^{-1}), and days to maturity (177.0), compared with the remaining treatments. However, the highest economic returns were achieved with the treatment of pendimethalin 30% EC at 1000 g ha^{-1} as a pre-emergence herbicide followed by two hand hoeings at 30 and 60 DAP (T_3), which generated a maximum net return of Rs 3,55,504 ha^{-1} and a benefit–cost ratio of 2.32. Therefore, proving this integrated weed management practice the most economically feasible and practical approach for garlic cultivation.

***Key words*:** Economics; garlic; hoeing; mulch; pendimethalin; yield

Introduction

Garlic is an important horticultural crop valued not only as a vegetable but also as a spice, condiment, and medicinal plant because of its distinctive flavour and wide range of therapeutic properties. Owing to its numerous health-promoting attributes, it is often referred to as the “wonder drug.” Garlic has been traditionally used for the prevention and management of several ailments, including hypertension, diabetes, peptic ulcers, rheumatism, helminthic infestations, bacterial and fungal infections, and certain types of cancer (Kilgori *et al*., 2007; Gupta *et al*., 2020). Garlic is an excellent source of vitamin C, sulphur, and modest levels of fat (Tarique *et al*., 2016). It also has about 29% carbs, 6.3% proteins, 0.3% minerals, and 0.1–0.4% essential oils. India is the world’s second-largest producer of garlic after China, with 392.15 thousand hectares under cultivation, yielding around 3,189.78 thousand tonnes at an average productivity of 8.14 MT ha^{-1}. About 0.99% of India’s total garlic production comes from Haryana. Garlic is grown on 3.20 thousand hectares of land in the state, yielding 31.70 thousand tons with an average productivity of 9.89 MT ha^{-1} (Anonymous, 2021). India is the world’s second-largest producer of garlic, although its average productivity is still far lower than that of a number of other top growing countries. Weed infestation is seen as

one of the biggest obstacles to garlic production among the many variables causing this disparity. Globally, weeds often referred to as the "silent enemies" of crops causes significant yield losses (Priya *et al*., 2017).

Weeds fiercely compete with garlic crops for vital resources such nutrients, soil moisture, light, and growing space, which lowers bulb quality and output while raising production and harvesting costs (Rahman *et al*., 2012). Due to its natural morphological and physiological traits, such as slow initial growth, short plant stature, non-branching growth habit, sparse foliage, and a shallow root system, the crop is especially vulnerable to weed competition during its early growth stages (Sahoo *et al*., 2018; Brewster and Rabinowitch, 2020). These traits create favourable conditions for weed emergence, establishment, and proliferation (Guerra *et al*., 2020; Paula *et al*., 2022). Yield losses caused by weeds in garlic have been reported to range from 30 to 60% (Kumar *et al*., 2013). In severe infestations where weeds remain uncontrolled until harvest, bulb yield may decline by as much as 88% (Singh *et al*., 2023).

Therefore, achieving larger yields and generating bulbs of marketable quality requires effective weed management throughout the crucial crop growth phase. However, because of labour shortages and operational limitations, farmers frequently find it challenging to remove weeds in a timely manner, which allows weeds to seriously harm crops. To address this challenge, various weed management approaches have been developed. Crop-weed competition can be reduced and crop biomass output can be increased by manual weeding (Islam *et al*., 2020). However, this process is labour-intensive, time-consuming, costly, and occasionally causes garlic bulbs to sustain mechanical damage. One of the most useful, affordable, and popular methods for managing weeds in garlic is chemical weed control. Numerous studies have shown that selective herbicides may efficiently reduce weeds and increase bulb output when used alone or in conjunction with manual weeding (Islam *et al*., 2020; Vishnu *et al*., 2015; Siddhu *et al*., 2018). Sustainable agricultural production is seriously threatened by the emergence of herbicide-resistant weed biotypes as a result of the frequent and careless application of herbicides (Shibayama, 2001). Consequently, the adoption of integrated, low-input and ecologically sustainable weed management strategies have become increasingly important for reducing reliance on synthetic herbicides while maintaining effective weed suppression and crop productivity (Riemens *et al*., 2022; Merfield, 2023).

Mulching has drawn a lot of interest as an environmentally beneficial cultural method for integrated weed control. In order to preserve soil moisture, control soil temperature, inhibit weed development, improve soil structure, boost microbial activity, lessen erosion, and encourage crop growth and production, it entails covering the soil's surface with organic or inorganic materials. Mulch improves the overall growing environment for a number of fruit and vegetable crops by minimizing evaporative water loss, reducing irrigation requirements, lowering soil salinity, and limiting soil-borne contamination in addition to effectively suppressing weeds (Yildiz *et al*., 2022; Üstüner *et al*., 2023; Imrak *et al*., 2024). In garlic, mulching has also been reported to enhance bulb yield and improve quality attributes such as total soluble solids, vitamin C content, and ash percentage. Considering the limitations associated with individual weed management practices and the potential benefits of integrated approaches, the present investigation was undertaken to evaluate the combined effects of crop residue mulch, cultural practices, and herbicide application on weed management, growth, yield and the economics of garlic production.

Material and Methods

In order to assess the combined effects of crop residue mulch, cultural practices, and herbicides on garlic cultivation, a field experiment was carried out during the *rabi* season of 2022–2023 at the Research Farm of the Department of Vegetable Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana. The sandy loam soil used in the experiment had a pH of 7.6 and was composed of 71.9% sand, 15.5% silt, and 12.6% clay. The soil contained 0.48% organic matter and 128.3 kg ha^{-1} of nitrogen, 15.5 kg ha^{-1} of phosphorus, and 224.8 kg ha^{-1} of potassium. Throughout the crop-growing season, all suggested agronomic techniques and plant protection measures were consistently used to guarantee robust crop development and efficient control of insect pests and diseases.

The experiment comprised fifteen treatments which were as follows: T_1: pendimethalin 30% EC @ 1000 g ha^{-1} as pre-emergence (PRE); T_2: pendimethalin 30% EC @ 1000 g ha^{-1} (PRE) followed by one hand hoeing at 30 days after planting (DAP); T_3: pendimethalin 30% EC @ 1000 g ha^{-1} (PRE) followed by two hand hoeings at 30 and 60 DAP; T_4: pendimethalin 30% EC @ 1000 g ha^{-1} (PRE) + crop residue mulch @ 6 t ha^{-1}; T_5: pendimethalin 30% EC @ 1000 g ha^{-1} (PRE) followed by one hand hoeing at 30 DAP + crop residue mulch @ 6 t ha^{-1}; T_6: oxadiargyl 6% EC @ 100 g ha^{-1} as early post-emergence (EPOST); T_7: oxadiargyl 6% EC @ 100 g ha^{-1} (EPOST) followed by one hand hoeing at 30 DAP;

Table 1: Effect of different weed management practices on growth attributes of garlic.

Treatments	Plant height (cm)			NLP	LL
	60 DAP	90 DAP	120 DAP		
T_1: Pendimethalin 30% EC @1000g/ha PRE	40.38	49.17	69.13	8.93	39.37
T_2: Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP)	41.70	51.81	69.93	9.26	39.55
T_3: Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP) + Hoeing (60 DAP)	45.86	58.94	76.67	10.10	41.04
T_4: Pendimethalin 30% EC @1000g/ha PRE + Mulching @ 6 t/ha	42.32	53.43	72.23	9.43	39.75
T_5: Pendimethalin 30% EC @1000g/ha PRE+ Hoeing (30 DAP) + Mulching @ 6 t/ha	45.11	58.17	75.37	9.67	41.02
T_6: Oxadiargyl 6% EC @100g/ha EPOST	39.62	48.80	68.20	8.70	38.88
T_7: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP)	40.53	50.94	69.83	9.20	39.52
T_8: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Hoeing (60 DAP)	43.71	56.91	74.67	9.63	40.97
T_9: Oxadiargyl 6% EC @100g/ha EPOST + Mulching @ 6 t/ha	41.96	53.29	71.21	9.30	39.73
T_{10}: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Mulching @ 6 t/ha	43.19	55.28	73.40	9.56	40.76
T_{11}: Mulching @ 6 t/ha	40.48	50.76	69.29	9.13	39.38
T_{12}: Hoeing (30 DAP) + Mulching @ 6 t/ha	42.46	54.17	72.59	9.46	40.11
T_{13}: Two hoeings (30 & 60 DAP)	42.53	54.63	73.11	9.53	40.36
T_{14}: Three hoeings (30, 60 & 90 DAP)	47.37	60.62	78.95	10.13	41.99
T_{15}: Weedy check (Control)	39.55	48.30	67.21	8.40	37.40
C.D. at 5%	**1.87**	**3.02**	**4.47**	**0.42**	**NS**
SEm±	**0.65**	**1.04**	**1.54**	**0.14**	**1.50**
C.V.	**2.63**	**3.35**	**3.69**	**2.66**	**5.31**

NLP: No. of leaves per plant; LL: Leaf length (cm); *PRE: Pre-emergence, EPOST: Early post-emergence, NS: Non significant

T_8: oxadiargyl 6% EC @ 100 g ha^{-1} (EPOST) followed by two hand hoeings at 30 and 60 DAP; T_9: oxadiargyl 6% EC @ 100 g ha^{-1} (EPOST) + crop residue mulch @ 6 t ha^{-1}; T_{10}: oxadiargyl 6% EC @ 100 g ha^{-1} (EPOST) followed by one hand hoeing at 30 DAP + crop residue mulch @ 6 t ha^{-1}; T_{11}: crop residue mulch alone @ 6 t ha^{-1}; T_{12}: one hand hoeing at 30 DAP + crop residue mulch @ 6 t ha^{-1}; T_{13}: two hand hoeings at 30 and 60 DAP; T_{14}: three hand hoeings at 30, 60, and 90 DAP; and T_{15}: weedy check. These treatments were arranged in RBD with three replications. The experimental plot size was 2.70 m × 2.70 m. The garlic variety HG-17 was planted manually on October 15, 2022 with seed rate of 4.0-5.0 q ha^{-1}, maintaining a spacing of 15 cm between rows and 10 cm between plants. Immediately after planting the cloves, light irrigation was applied to ensure uniform germination. In the specified treatments, pendimethalin was sprayed three days after planting as a pre-emergence herbicide, while oxadiargyl was sprayed twelve days after planting as an early post-emergence herbicide using a backpack sprayer equipped with a flat-fan nozzle. In the corresponding treatments, fenugreek residue mulch was spread right away after planting. Various observations on different growth parameters were recorded at different crop growth stages and the yield and yield-attributing characteristics were measured at harvest on April 16, 2023. Bulb yield and total plant biomass were recorded at harvest from the net plot area on hectare basis (q ha^{-1}). Economic performance was assessed using the prevailing local market price of garlic bulbs and the expenditure incurred on crop production. The benefit-cost ratio was determined as the ratio of gross returns to total cost of cultivation.

Data recorded on the different parameters were subjected to analysis of variance (ANOVA) under Randomized Block Design. The significance of treatment effects tested at 5% level of significance (pd”0.05) using OPSTAT statistical software. The usual methods outlined by Panse and Sukhatme (1967) were followed in the statistical analysis of the recorded data.

Results and Discussion

Effect on growth of garlic

Plant height and number of leaves are key phenological indicators of vegetative growth and overall growth development, as they directly reflect the plant’s capacity to intercept light, accumulate biomass and sustain physiological activity. In present study, weed management practices significantly affected the plant height and the number of leaves, whereas leaf length remains statistically unaffected (Table 1). Amongst the different treatments, the maximum plant height was consistently recorded with T_{14} (Three hoeings at 30, 60, and 90 DAP) at 60, 90, and 120 DAP (47.37 cm, 60.62 cm, and 78.95 cm, respectively). At 60DAP, T_{14} was statistically at par with T_3 (45.86 cm) and significantly superior to all the other

Table 2: Effect of different weed management practices on yield and yield attributes of garlic.

Treatments	PD	ED	NT	NCB	CL	ABW	BY	TPB	NDM
T_1: Pendimethalin 30% EC @1000g/ha PRE	3.85	4.36	6.81	29.30	2.39	24.15	70.97	89.16	166.3
T_2: Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP)	4.26	4.52	7.42	29.65	2.54	26.13	92.69	114.24	174.0
T_3: Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP) + Hoeing (60 DAP)	4.53	4.80	8.52	30.57	2.80	34.40	124.97	151.96	176.7
T_4: Pendimethalin 30% EC @1000g/ha PRE + Mulching @ 6 t/ha	4.30	4.59	7.56	29.83	2.58	28.65	104.31	126.72	170.6
T_5: Pendimethalin 30% EC @1000g/ha PRE+ Hoeing (30 DAP) + Mulching @ 6 t/ha	4.49	4.73	8.51	30.45	2.76	32.80	121.98	148.37	174.3
T_6: Oxadiargyl 6% EC @100g/ha EPOST	3.62	3.50	6.62	29.11	2.33	21.80	61.57	75.87	162.6
T_7: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP)	4.19	4.41	6.85	29.50	2.53	26.06	91.30	110.56	172.7
T_8: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Hoeing (60 DAP)	4.47	4.73	8.47	30.24	2.72	32.13	117.38	143.84	176.3
T_9: Oxadiargyl 6% EC @100g/ha EPOST + Mulching @ 6 t/ha	4.27	4.57	7.53	29.69	2.55	28.10	102.51	125.01	169.3
T_{10}: Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Mulching @ 6 t/ha	4.45	4.70	8.22	30.10	2.71	30.70	115.50	140.61	174.3
T_{11}: Mulching @ 6 t/ha	3.95	4.40	6.84	29.42	2.45	25.33	87.68	108.21	160.0
T_{12}: Hoeing (30 DAP) + Mulching @ 6 t/ha	4.31	4.60	7.92	29.95	2.59	29.03	107.12	129.53	171.3
T_{13}: Two hoeings (30 & 60 DAP)	4.38	4.61	8.16	30.00	2.69	29.70	110.52	135.61	175.0
T_{14}: Three hoeings (30, 60 & 90 DAP)	4.64	4.88	8.73	31.21	2.91	34.90	127.45	152.79	177.0
T_{15}: Weedy check (Control)	3.61	3.47	6.51	28.99	2.15	19.60	22.78	31.32	161.0
C.D. at 5%	**0.28**	**0.38**	**0.81**	**NS**	**0.11**	**4.06**	**8.40**	**7.07**	**3.46**
SEm±	**0.10**	**0.13**	**0.28**	**0.96**	**0.04**	**1.40**	**2.90**	**2.44**	**1.20**
C.V.	**3.92**	**5.14**	**6.38**	**5.54**	**2.51**	**8.60**	**5.16**	**3.56**	**1.21**

* PRE – Pre-emergence, EPOST- Early post-emergence, NS - Non significant.
PD: Polar diameter (cm); ED: Equatorial diameter(cm); NT: Neck thickness (mm); NCB: No. of cloves per bulb; CL: Clove length(cm); ABW: Average bulb weight(g); BY: Bulb yield(q/ha); TPB: Total plant biomass(q/ha); NDM: No. of days to maturity

treatments. However, at 90 and 120 DAP, T_{14} remains statistically comparable with T_3 (58.94 cm and 76.67 cm) and T_5 (58.17 cm and 75.37 cm). The maximum number of functional leaves per plant (10.13) was observed in T_{14}, which was at par with T_3 (10.10) and significantly higher than all other treatments. In contrast, leaf length did not vary significantly. Although, numerically the maximum leaf length was observed in T_{14} (41.99 cm), it was statistically at par with the all the treatments. This increase in growth parameters might be due to continuous removal of the weeds during the crop growth period which resulted in the poor crop-weed competition for moisture, nutrients and more sunlight exposure which in turn provided better growth environment for the garlic crop plants. Pendimethalin, a dinitroaniline, inhibits the microtubule assembly in meristematic tissues, providing effective control of annual grasses and broad-leaved weeds during the first 30-40 DAP. Integration of Pendimethalin with hand hoeing further extends the weed-free period to 60-75 DAP, which coincides with the critical crop-weed competition period reported for short-statured bulb crops (Das *et al*., 2020; Chopra *et al*., 2023). Meanwhile, the weedy check reported poor growth and development leading to the lowest plant height (39.55cm, 48.30cm and 67.21cm, respectively) at 60, 90 and120 DAP, as well as the number of leaves per plant (8.40). This might be due to severe crop weed competition that led to uncontrolled weed growth, inadequate sunshine exposure, and competition for nutrients and water throughout the crop's growing season in weedy check (control) plot which hampered the crop's growth parameters. Similar finding has been reported in bulb crops by Vishnu *et al*., (2015), Bhasker *et al*., (2024), Paikra *et al*., (2022), Gupta *et al*., (2019), Chattopadhyay *et al*., (2016), Mohite *et al*., (2015) and Channapagoudar and Biradar. (2007).

Effect on yield and yield attributes of garlic

The effect of different weed management practices on yield and yield attributing parameters was significant ($p \leq 0.05$) except for number of cloves per bulb (Table 2).

Table 3: Effect of different weed management practices on economics of garlic .

Treatments	Yield (q/ha)	Cost of cultivation (Rs. /ha)	Gross Returns (Rs. /ha)	Net Returns (Rs. /ha)	B:C Ratio
T_1 : Pendimethalin 30% EC @1000g/ha PRE	70.97	234346	354850	120504	1.51
T_2 : Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP)	92.69	251846	463450	211604	1.84
T_3 : Pendimethalin 30% EC @1000g/ha PRE + Hoeing (30 DAP) + Hoeing (60 DAP)	124.97	269346	624850	355504	2.32
T_4 : Pendimethalin 30% EC @1000g/ha PRE + Mulching @ 6 t/ha	104.31	262346	521550	259204	1.99
T_5 : Pendimethalin 30% EC @1000g/ha PRE+ Hoeing (30 DAP) + Mulching @ 6 t/ha	121.98	279846	609900	330054	2.18
T_6 : Oxadiargyl 6% EC @100g/ha EPOST	61.57	234413	307850	73437	1.31
T_7 : Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP)	91.30	251913	456500	204587	1.81
T_8 : Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Hoeing (60 DAP)	117.38	269413	586900	317487	2.18
T_9 : Oxadiargyl 6% EC @100g/ha EPOST + Mulching @ 6 t/ha	102.51	262413	512550	250137	1.95
T_{10} : Oxadiargyl 6% EC @100g/ha EPOST + Hoeing (30 DAP) + Mulching @ 6 t/ha	115.50	279913	577500	297587	2.06
T_{11} : Mulching @ 6 t/ha	87.68	260046	438400	178354	1.69
T_{12} : Hoeing (30 DAP) + Mulching @ 6 t/ha	107.12	277546	535600	258054	1.93
T_{13} : Two hoeings (30 & 60 DAP)	110.52	267046	552600	285554	2.07
T_{14} : Three hoeings (30, 60 & 90 DAP)	127.45	284546	637250	352704	2.24
T_{15} : Weedy check (Control)	22.78	232046	113900	-118146	0.49

It is evident from the results that three hoeings at 30, 60 and 90 DAP recorded maximum yield and yield attributing parameters *viz.*, polar diameter (4.64 cm), equatorial diameter (4.88 cm), neck thickness (8.73 mm), number of cloves per bulb (31.21), clove length (2.91 cm), average bulb weight (34.90 g), bulb yield (127.45 q/ha), total plant biomass (152.79 q/ha) and number of days to maturity (177.0). For polar diameter, T_{14} (4.64cm) was statistically at par with T_3 (4.53cm), T_5 (4.49cm), T_8 (4.47cm), T_{10} (4.45cm) and T_{13} (4.38cm). Equatorial diameter showed wider adaptability, where T_{14} (4.88cm) was at par with T_3 (4.80cm), T_5 (4.73cm), T_8 (4.73cm), T_{10} (4.70cm), T_{13} (4.61cm), T_{12} (4.60cm), T_4 (4.59cm), T_9 (4.57cm), T_2 (4.52cm). Similarly, Neck thickness under T_{14}(8.73cm) was found at par with T_3 (8.52mm), T_5 (8.51mm), T_8 (8.47mm), T_{10} (8.22mm), T_{13} (8.16mm), T_{12} (7.92mm).

Number of cloves per bulb was not significantly influenced by the different weed management practices, ranging from 28.99 (T_{15}) to 31.21 (T_{14}), suggesting it is a stable genotypic character. In contrast, clove length and average bulb weight varied significantly. The maximum clove length was recorded with T_{14} (2.91cm) which was found statistically at par with T_3 (2.80cm). Similarly, T_{14} produced the maximum average bulb weight (34.90g), which was statistically comparable to T_3 (34.40g), T_5 (32.80g) and T_8 (32.13g).

Bulb yield is the principle economic trait and the ultimate indicator of the effectiveness of weed management practices, as it reflects the cumulative influence of crop growth, resource utilization and the degree of weed interference throughout the crop growth cycle. Bulb yield and total plant biomass, which largely determine garlic productivity, differed significantly among the weed management treatments. T_{14} produced the highest bulb yield (127.45 q ha^{-1}) and total biomass (152.79 q ha^{-1}), which was statistically comparable with T_3 (124.97 and 151.96 q ha^{-1}) and T_5 (121.98 and 148.37 q ha^{-1}), respectively.

Combining hand hoeing with pre-and post-emergence herbicide application enhanced the persistence of weed suppression, extending the effective control period and minimizing weed interference during the critical stages of crop growth. The enhanced growth, yield and yield attributes in T_{14} might be attributed to continuous hand weeding throughout the crop growth phase, which minimized weed-crop competition and reduced the depletion of soil nutrients by weeds. The resulting greater availability of nutrients and other growth resources to the crop likely promoted better bulb development, as reflected in the higher polar, equatorial diameters and neck thickness (Gupta *et al.*, 2019; Gandolkar *et al.*, 2015). Garlic plants exhibited vigorous growth, rapidly expanding leaf canopies and roots that were efficiently utilizing the resources necessary for plant growth. This improved bulb development which increased the clove

length and average clove weight (Ramani and Khanpara, 2010). The maximum yield in T14 appears to be the result of the favourable environment created by clean crop culture, which leads to more absorption of solar radiation, plant nutrients, increased photosynthetic rates, increased supply of carbohydrates, accumulation of dry matter in cloves, and ultimately better vegetative growth of the plant, which in turn exhibited better bulb development and hence better bulb yield (Bhasker *et al*., 2024). Furthermore, improved weed control results in plants with greater height and more assimilates that are generated, translocated, and stored in plant organs, each of which contribute to a positive impact on bulb yield. These results were in close conformity with earlier findings reported in garlic (Ramani and Khanpara, 2010; Sampat *et al*., 2014). However, the detrimental effect of weeds caused a reverse trend in the weedy check (control) resulting in the lowest recorded yield and yield attributing parameters in the plot. Weed management methods influence plant growth, development, and yield by increasing nutrient availability for the crop. The findings are consistent with previous studies done in bulb crops by Islam *et al*. (2020), Vishnu *et al*., (2015), Chattopadhyay *et al*., (2016) and Sampat *et al*., (2014).

Days to maturity were significantly affected by weed management practices. T_{14} recorded the longest maturity period (177.0 days), and was statistically at par with T_3 (176.7 days), T_8 (176.3 days), T_{13} (175.0 days), T_5 (174.3 days) and T_{10} (174.3 days) and T_2 (174.0 days). In contrast, the garlic plants in the weedy check matured earliest (161.0 days), followed closely by mulching alone (T_{11}, 160.0 days). T_{14} also recorded the maximum number of days to maturity owing to lesser crop-weed competition due to which crop plants were able to utilize the nutrients, water, space, sunlight efficiently and hand hoeing which provided aeration to deeper soil layers (Patil *et al*., 2016). The earlier maturity under weedy conditions may be associated with stree-induced forced maturity due to resource limitation. Decomposing straw releases phenolic acids like ferulic and p-coumaric acid, which at higher concentrations inhibits the root growth of garlic. Moreover, continuous mulch keeps soil excessively moist and cool during the early phase, delaying the initial growth, but later creates anaerobic microenvironment at the collar region, promoting early neck softening and forced maturity. This is in conformity with Karimi *et al*., (2020) and El-Shaieny *et al*., (2022) who reported 7-10 days early maturity under sole mulching without supplementary weeding in Alliums.

Economics

In view of economics of garlic crop (Table 3) highest net returns (Rs.3,55,504/ha) and B:C ratio (2.32) was recorded with the application of pendimethalin 30% EC @1000g/ha PRE + two hoeings at 30 and 60 DAP. This might be due to the lower cultivation costs associated with this treatment compared to treatment of three hoeings. The treatment of three hoeings recorded the maximum total bulb yield (127.45 q/ha) and gross returns (Rs.6,37,250/ ha) while, the net returns (Rs.3,52,704/ha) and B:C ratio (2.24) was lower than treatment of pendimethalin 30% EC @1000g/ha PRE + two hoeings at 30 and 60 DAP. This could be due to frequent hand hoeing operations, which required more labour in order to eradicate the weeds. This increased the costs of weeding, which in turn increased the overall cost of cultivation of T14 (Gupta *et al*., 2020; Chaudhari *et al*., 2024). However, the lowest net return (Rs. -1,18,146/ ha) and B:C ratio (0.49) was noticed in the weedy check treatment. These results are in close agreement with earlier reports in onion and garlic crops by Kumar *et al*., (2013) and Sampat *et al*., (2014).

Conclusion

The study showed that combining herbicide application with timely hand weeding improved garlic growth, yield attributes, and bulb yield. The application of three hoeings at 30, 60, and 90 DAP, resulted in the maximum growth, bulb yield, and yield-attributing parameters, which remained statistically at par with pendimethalin 30% EC @1000g/ha as pre-emergence + two hoeings at 30 and 60 DAP for several growth and yield parameters. The pre-emergence application of pendimethalin 30% EC @1000g/ha + two hoeings at 30 and 60 DAP, resulted in a higher net return (Rs. 3,55,504/ ha) and benefit ratio (2.32) than three hoeings at 30, 60, and 90 DAP, indicating better economic efficiency under the prevailing input and labour costs. Thus, three hoeings at 30, 60, and 90 DAP, offers a practical approach for achieving higher garlic productivity, while pendimethalin 30% EC @1000g/ha as pre-emergence + hoeing at 30 and 60 DAP can be economically efficient option for garlic production.

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Authors' contributions

Sonia conducted the field experiment and contributed in Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing original draft, review and editing of the manuscipt. Makhan Lal contributed to conceptualisation, methodology, review and supervision. P. Bhasker and Kuldeep Kumar contributed in Validation and writing – review and editing. All authors read and approved the final manuscript.

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