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Sustainable Weed Management Practices in Growth and Yield of Soybean *(Glycine max L.)*

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Soybean productivity is substantially affected by weed competition, particularly during the early stages of crop growth when weeds compete for essential resources. Effective and sustainable weed-management strategies are therefore important for reducing weed interference and improving soybean growth and yield performance. An experiment was conducted during the *kharif* season of 2025-26 at the College Farm, School of Agricultural Sciences, G H Raisoni University, Saikheda, PM, to evaluate sustainable weed-management practices in soybean (*Glycine max* L.). The experiment was laid out in a randomised block design with three replications. The evaluated treatments comprised post-emergence quizalofop-p-ethyl; pendimethalin followed by imazethapyr, fenoxaprop-p-ethyl, quizalofop-p-ethyl, or halosulfuron; pendimethalin followed by hand weeding or wheel-hoe weeding; a weed-free treatment involving hand weeding at 20 and 40 DAS; and a weedy check. Observations were recorded on crop growth and yield-attributing characters. Plant height and plant dry-matter accumulation did not differ significantly among treatments at 30 DAS, but treatment effects became significant at later growth stages. The weed-free treatment consistently produced the greatest plant height and dry-matter accumulation, while several integrated weed-management treatments were statistically comparable for selected observations. The weed-free treatment also recorded the highest number of filled pods, total pods, and seeds per pod, whereas the weedy check generally showed poorer growth and reproductive performance. The number of unfilled pods and 100-

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seed weight were not significantly affected by the treatments. Overall, sustained weed suppression during critical crop-growth stages improved soybean growth and important yield-attributing characters under the conditions of the experiment.

Keywords: Soybean; Glycine max L.; weed management; pendimethalin; quizalofop-p-ethyl; imazethapyr; integrated weed management; hand weeding; crop growth; yield attributes.

1. Introduction

Soybean (*Glycine max* (L.) Merrill) is a member of the family Leguminosae and subfamily Papilionoideae, with 2n = 40. Native to East Asia and popularly known as the "Golden bean", it has become the miracle crop of the 21st century. This crop is successfully grown in climatic regions with hot summers, with optimum growing conditions at a mean temperature of 20-30°C. It serves a dual purpose, being grown both as an oilseed crop and as a pulse crop (Thakare *et al*., 2006). It is an excellent source of protein and oil; additionally, it contains high levels of amino acids such as lysine, leucine, and lecithin, as well as a large amount of phosphorus. Soybean contains approximately 40-45 % protein and 18-22 % oil (Goyal *et al*., 2012) and is a rich source of vitamins and minerals. Soybean crop ranks first as a source of vegetable oil in the world.

Effective weed management is especially important during early soybean development because weed interference during the critical period can reduce crop resource capture and ultimately depress yield; maintaining an adequately weed-free period through the early vegetative stages has therefore been identified as a key component of soybean production (Van Acker et al., 1993). Field studies in soybean further indicate that integrated approaches combining timely herbicide application with mechanical or manual weeding can reduce weed biomass while improving crop growth and productivity (Jadhav & Kashid, 2019; Roy et al., 2023). Recent evidence also shows that effective pre-emergence and integrated weed-management programmes can improve plant height, dry-matter accumulation, and seed yield by limiting competition for light, moisture, nutrients, and space (Gajendra et al., 2023). National agricultural statistics provide the broader production context for soybean and other oilseed crops in India (Department of Agriculture & Farmers Welfare, 2025).

More recent field evidence further indicates that extending weed suppression through residual or sequential programmes can protect soybean growth and yield by delaying damaging weed interference. Residual pre-emergence herbicide mixtures have been shown to postpone the onset of the critical period of weed control (Roncatto et al., 2023), while sequential pendimethalin followed by imazethapyr reduced weed density and biomass and improved soybean growth and yield under rainfed conditions (Zion et al., 2025). Effective post-emergence weed control has likewise been associated with greater soybean growth where competition was reduced during early development (Kumar et al., 2026). Recent comparative field work has also evaluated pendimethalin, metribuzin and imazethapyr, alone or in sequence, alongside manual weeding for their effects on weed biomass, soybean growth and yield, supporting the value of comparing chemical and manual weed-management options under field conditions (Pokhrel et al., 2025).

From a farm-management perspective, herbicide adoption in soybean has also been associated with the practical objective of reducing the labour burden of manual hoeing, indicating that operational considerations are relevant when selecting weed-control strategies (Jain et al., 2025). Under kharif conditions, early post-emergence herbicide programmes have been evaluated against hand weeding for weed suppression and soybean performance, with treatment response varying according to the herbicide regime (Das & Samui, 2024). Application technology may also influence operational performance, as comparisons of knapsack, boom and drone sprayers in soybean have demonstrated differences in weed-control and application efficiency (Hiremath et al., 2024). Recent multi-site research further indicates that crop configuration and herbicide programme can jointly influence weed suppression, with PRE followed by POST herbicide programmes providing consistent weed control across planting scenarios (Goddard et al., 2025).

However, the relative performance of the specific weed-management options examined in the present experiment—single post-emergence herbicide use, pendimethalin-based sequential treatments, manual or mechanical follow-up weeding, weed-free management, and a weedy check—required direct comparison under the local kharif conditions of the study site.

Objective: The objective of the present study was to evaluate the effects of these weed-management practices on soybean weed dry matter, crop growth parameters, yield attributes, and yield under kharif 2025-26 conditions at the College Farm, School of Agricultural Sciences, G H Raisoni University, Saikheda, PM.

2. Materials and Methods

An experiment was conducted on Sustainable weed management practices in Soybean (*Glycine max* L.) at College Farm, School of Agricultural Sciences, G H Raisoni University, Saikheda, PM, during the *kharif* season of 2025-26. The experiment was laid out in a randomised block design and replicated thrice. The experiment consisted of twelve treatments *viz*., T_1: Quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS, T_2: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* imazethapyr @ 100 g a.i./ha at 20 DAS, T_3: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* fenoxaprop-p-ethyl @ 80 g a.i./ha at 20 DAS, T_4: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS, T_5: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* halosulfuron @ 67.5 g a.i./ha at 20 DAS, T_6: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* hand weeding at 40 DAS, T_7: Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* weeding by wheel hoe at 40 DAS, T_8: Weed-free (hand weeding twice at 20 DAS and at 40 DAS), T_9: Weedy check. The observations were recorded for weed dry matter, crop growth parameters, yield attributes, and yield.

The treatment structure provided a direct comparison among different weed-management approaches under the same experimental conditions. T1 represented a sole post-emergence herbicide treatment, with quizalofop-p-ethyl applied at 20 DAS. Treatments T2 to T5 followed a sequential chemical approach in which pendimethalin was used as a pre-emergence herbicide and was followed at 20 DAS by imazethapyr, fenoxaprop-p-ethyl, quizalofop-p-ethyl, or halosulfuron, respectively. Treatments T6 and T7 combined pre-emergence pendimethalin with a later non-chemical operation at 40 DAS, comprising hand weeding in T6 and wheel-hoe weeding in T7. The weed-free treatment (T8) involved hand weeding at both 20 and 40 DAS, whereas T9 served as the weedy check. Thus, the treatment arrangement allowed chemical, sequential chemical, integrated chemical-manual or mechanical, weed-free, and untreated weed-management conditions to be assessed within the randomised block design.

Observations were recorded to characterise crop growth and yield-related responses to the weed-management treatments. Plant height and plant dry-matter accumulation were assessed at 30, 60, and 90 DAS and again at harvest, thereby covering successive stages of crop development. Yield-attributing characters comprised filled pods per plant, unfilled pods per plant, total pods per plant, seeds per pod, and 100-seed weight. Weed dry matter and yield were also included among the variables recorded in the experiment. The weed-free treatment and the weedy check provided contrasting reference conditions for interpreting the crop response to reduced or continued weed interference, while the remaining treatments represented the different herbicidal, manual, and mechanical weed-management options evaluated in the study.

3. Results and Discussion

3.1 Plant Height (cm)

At early growth (30 DAS), weed control practices exerted no statistically significant impact on plant height. However, numerical values peaked under T_4 (24.45 cm) and were lowest in the unweeded control T_9 (21.95 cm).

By 60 DAS, the weed-free treatment (T_8) achieved superior height (44.80 cm), performing at par with T_6 (42.60 cm), T_4 (42.50 cm), T_3 (42.20 cm), and T_7 (40.30 cm), whereas T_9 resulted in significantly stunted growth (30.90 cm). At 90 DAS, T_8 maintained maximum height (58.10 cm), remaining statistically comparable to T_6 (56.60 cm), T_4 (55.30 cm), T_3 (54.90 cm), T_7 (54.50 cm), T_1 (53.20 cm), and T_2 (52.90 cm), with T_9 registering the minimum height (43.20 cm).

At harvest, trends remained consistent: T_8 produced the tallest plants (58.70 cm), which were on par with T_6 (56.90 cm), T_4 (55.80 cm), T_3 (55.30 cm), T_7 (55.00 cm), T_1 (53.60 cm), and T_2 (53.30 cm), while T_9 recorded the lowest value (43.40 cm).

The greater plant height recorded under the weed-free and integrated weed-management treatments is consistent with the reduction in interspecific competition expected when weeds are suppressed during the crop's active vegetative phase. Similar soybean studies have reported improved plant height and growth where weed density and biomass were reduced through integrated herbicidal and cultural practices (Gajendra et al., 2023; Roy et al., 2023). Jadhav and Kashid (2019) likewise observed that combining chemical and manual weed control reduced weed biomass and supported higher soybean productivity, indicating that sustained weed suppression can favour more efficient use of growth resources. Accordingly, the lower plant height under the weedy check in the present experiment may reasonably be attributed to prolonged competition for light, water, nutrients, and rooting space rather than to a direct treatment effect on stem elongation alone.

Recent field studies provide additional support for this pattern. Greater soybean plant height was recorded where sequential pendimethalin followed by imazethapyr effectively suppressed weeds (Zion et al., 2025), and maximum plant height was also observed under two hand weedings, with an effective post-emergence herbicide programme producing comparable crop growth (Kumar et al., 2026). These findings are consistent with the present observation that treatments maintaining lower weed pressure were associated with greater plant height than the weedy check.

Table 1. Plant height (cm) at different growth stages as influenced by different treatments

Treatments	Plant height (cm)			
	30 DAS	60 DAS	90 DAS	At harvest
T_1 -Quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	23.15	39.10	54.00	54.60
T_2-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* imazethapyr @ 100 g a.i./ha at 20 DAS.	23.85	38.65	53.40	54.00
T_3-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* fenoxaprop-p-ethyl @ 80 g a.i./ha at 20 DAS.	24.25	42.75	55.80	56.40
T_4-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	24.45	43.05	56.30	56.90
T_5-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* halosulfuron @ 67.5 g a.i./ha at 20 DAS	23.35	36.55	50.90	51.50
T_6-Pendimethalin @ 1.0 kg a.i./ha as pre- emergence *fb* hand weeding at 40 DAS.	23.80	43.45	57.50	58.00
T_7-Pendimethalin @ 1.0 kg a.i./ha as pre- emergence *fb* weeding by wheel hoe at 40 DAS	23.55	40.85	55.20	55.75
T_8-Weed free (hand weeding twice at 20 DAS and at 40 DAS).	23.95	45.25	59.20	59.80
T_9-Weedy check.	21.95	31.35	43.80	44.10
SEm ±	1.24	1.92	2.10	2.15
CD (P=0.05)	NS	5.60	6.14	6.27

3.2 Plant Dry Matter (g/plant)

Dry matter accumulation per plant showed no significant treatment variation at 30 DAS. The numerical maximum occurred in T_4 (2.99 g/plant) and the minimum in T_9 (2.44 g/plant).

At 60 DAS, dry matter production differed significantly, with T_8 accumulating the highest biomass (12.43 g/plant), which was at par with T_6 (11.53 g/plant), T_4 (11.31 g/plant), and T_3 (10.98 g/plant). Uncontrolled weed competition in T_9 yielded the lowest dry mass (7.31 g/plant).

This trend continued at 90 DAS, where T_8 (18.18 g/plant) remained statistically equivalent to T_6 (16.99 g/plant), T_4 (16.73 g/plant), and T_3 (16.23 g/plant), while T_9 recorded 10.72 g/plant. At final harvest, T_8 again recorded peak dry matter (18.38 g/plant), closely followed by T_6 (17.15 g/plant), T_4 (16.89 g/plant), and T_3 (16.38 g/plant), whereas T_9 lagged significantly (14.28 g/plant).

The higher dry-matter accumulation under T8 and the statistically comparable integrated treatments suggest that effective weed suppression allowed a greater proportion of available resources to be converted into crop biomass. This interpretation agrees with reports that lower weed density and weed dry matter are associated with improved soybean dry-matter production and yield under integrated management (Gajendra et al., 2023; Roy et al., 2023). The response is also compatible with the critical-period concept in soybean, whereby early and sustained removal of competing vegetation protects crop growth during stages when yield potential is being established (Van Acker et al., 1993). Thus, the lower biomass observed in the weedy check is consistent with cumulative resource competition across the growing period.

Recent evidence also indicates that improved weed control can be reflected in greater soybean biomass accumulation. Sequential pendimethalin followed by imazethapyr increased crop dry-matter production while reducing weed biomass (Zion et al., 2025), whereas intensive hand weeding and an effective post-emergence herbicide programme produced greater shoot dry matter than the weedy check (Kumar et al., 2026). In addition, residual herbicide mixtures can delay the onset of damaging weed interference (Roncatto et al., 2023), providing a plausible agronomic basis for sustaining biomass accumulation during early crop development.

Table 2. Plant dry matter (g/plant) at different growth stages as influenced by different treatments

Treatments	Plant dry matter (g/plant)			
	30 DAS	60 DAS	90 DAS	At harvest
T_1 -Quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	2.75	9.99	15.04	15.18
T_2 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* imazethapyr @ 100 g a.i./ha at 20 DAS.	2.77	9.94	14.92	15.05
T_3 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* fenoxaprop-p-ethyl @ 80 g a.i./ha at 20 DAS.	2.92	10.98	16.23	16.38
T_4 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	2.99	11.31	16.73	16.89
T_5- Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* halosulfuron @ 67.5 g a.i./ha at 20 DAS	2.71	9.33	14.04	14.13
T_6-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* hand weeding at 40 DAS.	2.67	11.53	16.99	17.15
T_7-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* weeding by wheel hoe at 40 DAS	2.70	10.66	15.84	15.97
T_8-Weed free (hand weeding twice at 20 DAS and at 40 DAS).	2.93	12.43	18.18	18.38
T_9-Weedy check.	2.44	7.31	10.72	10.78
SEm ±	0.3	0.59	0.76	0.79
CD (P=0.05)	NS	1.73	2.23	2.31

3.3 Yield Attributes

- **Filled Pods per Plant:** Weed control measures significantly affected pod formation. T_8 produced the highest number of filled pods (28.35), which was statistically comparable to T_6 (25.40) and T_4 (24.90), whereas T_9 recorded the lowest (15.95).
- **Unfilled Pods per Plant:** Treatments showed no statistically significant effect on unfilled pod count. However, T_9 exhibited the highest number of unfilled pods (13.35), while T_8 maintained the lowest count (10.55).
- **Total Pods per Plant:** Total pod count responded significantly to weed control. The weed-free check (T_8) recorded the maximum total pod count (38.90), which was at par with T_6 (36.35), T_3 (36.25), and T_4 (36.10). T_9 produced the fewest pods (29.30).

Seeds per Pod: Treatment variations significantly affected seed numbers per pod. T_8 yielded the highest seed count (2.28), and all herbicide/cultural treatments performed at par with it except T_9, which recorded a minimum of 1.54 seeds/pod.

100-Seed Weight (g): Test weight (100-seed weight) was not significantly altered by treatment regimes. Values ranged from a high of 9.55 g in T_8 to a low of 8.96 g in T_9.

The improvement in filled pods, total pods, and seeds per pod under effective weed control indicates that reduced weed interference benefited reproductive development, while the non-significant response of 100-seed weight suggests that treatment effects were expressed more strongly through pod and seed number than through individual seed mass. Comparable soybean experiments have shown that weed-free conditions and integrated weed-management treatments improve yield attributes and grain yield by reducing weed competition during critical growth stages (Jadhav & Kashid, 2019; Roy et al., 2023). Gajendra et al. (2023) similarly reported higher soybean growth and yield under treatments that substantially reduced weed density and biomass. These findings support the present pattern in which T8 achieved the most favourable reproductive attributes, whereas continuous weed interference in T9 was associated with fewer filled and total pods and fewer seeds per pod.

Evidence from field studies indicates that weed interference can be expressed strongly through soybean reproductive components. Continuous weed interference reduced pod number and thousand-grain weight, whereas timely weed control maintained more favourable yield components (Caldas et al., 2023). Earlier work similarly found that pod number was more sensitive to weed competition than seeds per pod or grain weight (Silva et al., 2009), and modelling studies have confirmed progressive soybean yield reductions as weed interference increases (Song et al., 2021). This evidence is consistent with the present response of pod and seed-number traits, while the non-significant response of 100-seed weight suggests comparatively lower sensitivity of individual seed mass under the treatments evaluated.

Table 3. Yield-attributing characters as influenced by different treatments

Treatments	Filled Pods per Plant	Unfilled Pods per Plant	Total Pods per Plant	Seeds per pod	100-seed weight (g)
T_1 -Quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	23.10	12.20	35.30	2.20	9.46
T_2 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* imazethapyr @ 100 g a.i./ha at 20 DAS.	22.70	12.45	35.15	2.18	9.43
T_3 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* fenoxaprop-p-ethyl @ 80 g a.i./ha at 20 DAS.	24.60	11.65	36.25	2.22	9.50
T_4 -Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* quizalofop-p-ethyl @ 50 g a.i./ha at 20 DAS	24.90	11.15	36.10	2.24	9.51
T_5- Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* halosulfuron @ 67.5 g a.i./ha at 20 DAS	19.60	12.75	32.35	2.03	9.39
T_6-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* hand weeding at 40 DAS.	25.40	10.95	36.35	2.25	9.52
T_7-Pendimethalin @ 1.0 kg a.i./ha as pre-emergence *fb* weeding by wheel hoe at 40 DAS	23.35	11.55	34.90	2.21	9.47
T_8-Weed free (hand weeding twice at 20 DAS and at 40 DAS).	28.35	10.55	38.90	2.28	9.55
T_9-Weedy check.	15.95	13.35	29.30	1.54	8.96
SEm ±	1.29	0.80	1.25	0.11	0.22
CD (P=0.05)	3.76	NS	3.66	0.33	NS

4. Conclusions

Weed-management practices significantly influenced soybean growth and several yield-attributing characters under the conditions of the experiment. The weed-free treatment involving hand weeding at 20 and 40 DAS produced the greatest plant height and dry-matter accumulation during later crop growth and recorded the highest filled pods, total pods and seeds per pod. Several integrated treatments involving pendimethalin followed by herbicidal, manual or mechanical weed control produced statistically comparable responses for selected growth and yield attributes. Continuous weed interference resulted in generally poorer crop growth and reproductive performance. In contrast, 100-seed weight was not significantly affected by the evaluated treatments. These results indicate that maintaining effective weed suppression during critical stages of soybean development is important for improving crop growth and yield-attributing characteristics.

5. Limitations

The study was conducted at a single location during one kharif season with three replications, so treatment responses may vary under other soils, climates, seasons, and soybean production environments. The experiment evaluated a defined set of chemical, manual, and mechanical weed-management options; therefore, the conclusions are limited to those treatments and the measured growth and yield attributes. Multi-location and multi-season trials with broader environmental representation would help determine the consistency and wider applicability of the observed responses.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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