

Development and field evaluation of a precision inter-row herbicide applicator for improving herbicide application efficiency, crop safety and weed management in vegetable pea (*Pisum sativum* L.)

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Development and field evaluation of a precision inter-row herbicide applicator for improving herbicide application efficiency, crop safety and weed management in vegetable pea (*Pisum sativum* L.)

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Highlights

- A precision inter-row herbicide applicator (IRHA) was developed for post-emergence (PoE) herbicide application in vegetable pea.
- Precision inter-row application reduced weed density and biomass while minimizing crop exposure to herbicides.
- IRHA improved weed control efficiency compared with conventional post-emergence herbicide application.
- Precision herbicide placement enhanced crop growth and green pod yield in vegetable pea.
- IRHA increased economic returns and the benefit:cost ratio.

Abstract

Background

Weed infestation is a major constraint to vegetable pea (*Pisum sativum* L.) production because intense crop–weed competition reduces crop growth and productivity. Although sequential herbicide application is widely used, conventional post-emergence (PoE) spraying may result in non-uniform herbicide deposition and unintended crop exposure.

Objective

To evaluate the performance of a precision inter-row herbicide applicator (IRHA) for post-emergence (PoE) application of imazethapyr following pre-emergence (PE) pendimethalin in vegetable pea.

Methods

A two-year field experiment was conducted during the *rabi* seasons of 2023–24 and 2024–25 at the Agronomic Research Farm of Ranjeet Singh Memorial (P.G.) College, Dhampur, Uttar Pradesh, India. The experiment was arranged in a randomized complete block design (RCBD) with seven treatments and three replications. Pendimethalin was applied as a pre-emergence (PE) herbicide at **1.0 kg a.i. ha⁻¹**, followed by (*fb*) post-emergence (PoE) application of imazethapyr at **60 g a.i. ha⁻¹** using different application methods.

Results

The weed-free treatment recorded the highest weed suppression and crop productivity. Among the herbicide-based treatments, sequential application of **PE pendimethalin fb PoE imazethapyr through IRHA (T₄)** provided superior weed control, improved crop growth, and increased green pod yield compared with conventional PoE application methods. Precision application also resulted in higher economic returns and higher benefit - cost ratio.

Conclusion

These findings demonstrate that the IRHA is a promising precision herbicide application technology for improving weed management and productivity in vegetable pea while enhancing the efficiency of PoE herbicide application.

Keywords: Precision herbicide application; Inter-row herbicide applicator; Vegetable pea; Weed management; Pendimethalin; Imazethapyr.

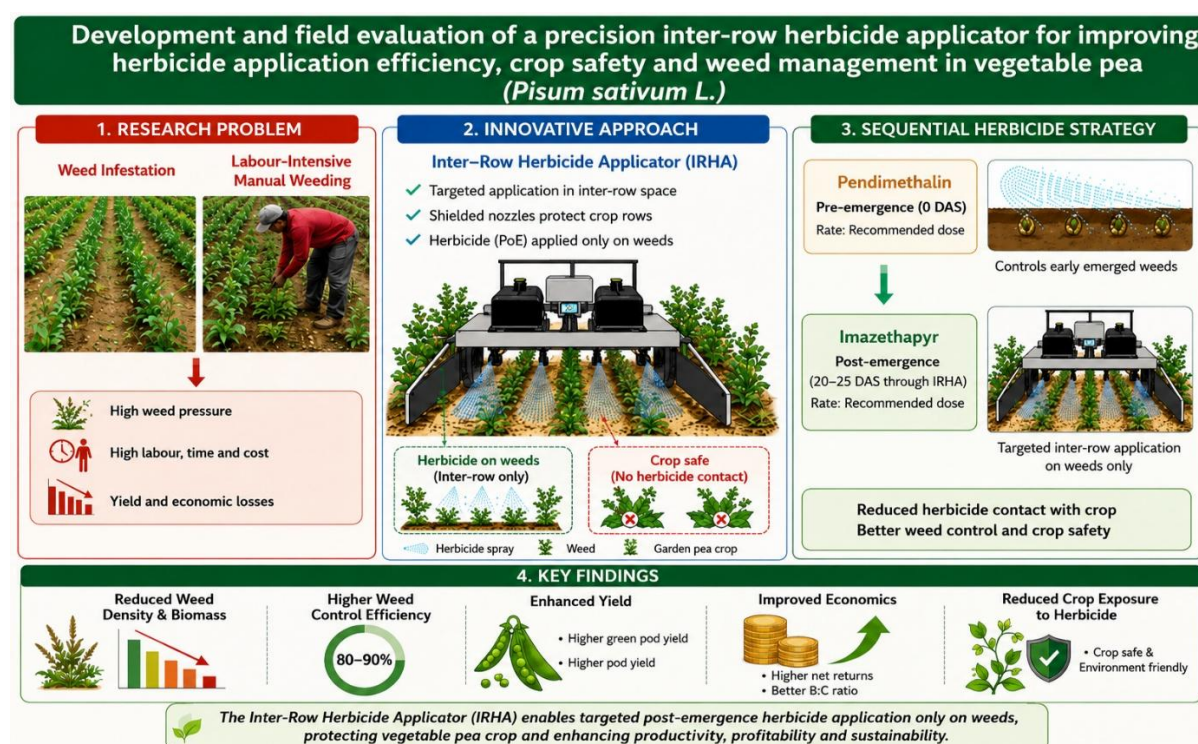


Fig. 1 Graphical abstract: Application of pendimethalin and imazethapyr via inter-row applicator reduced weeds, enhanced weed control efficiency, improved growth and yield, and increased economic returns in cultivated pea crop.

INTRODUCTION

Vegetable pea (*Pisum sativum* L.) is an important cool-season leguminous crop cultivated worldwide for fresh pod consumption and dry seed production. Globally, it occupies approximately 2.66 million ha with an annual production of 21.48 million tonnes and an average productivity of 8.07 t ha⁻¹ (FAOSTAT 2023). India is the second-largest producer after China, cultivating vegetable pea over about 0.56 million ha with an annual production of 5.84 million tonnes and an average productivity of 10.30 t ha⁻¹ (DA&FW 2021). Among Indian states, Uttar Pradesh contributes the largest share of both cultivated area and production (DA and FW, 2021). Besides its economic importance, vegetable pea is a rich source of protein, carbohydrates, vitamins, and minerals, and, as a leguminous crop, contributes to soil fertility

through biological nitrogen fixation, leaving approximately 50–60 kg ha⁻¹ residual nitrogen in the soil (Negi et al. 2006; Peter and Pranab 2012; Thamburaj and Singh 2013).

Weed infestation is one of the major constraints limiting vegetable pea productivity because the crop exhibits slow initial growth, limited canopy development, and poor competitive ability during the early growth stages. Consequently, severe crop–weed competition for nutrients, moisture, light, and space may reduce pod yield by 40–70% under heavy weed infestation (Harker et al. 2001; Johnson and Holm 2010). The critical period of weed competition in vegetable pea generally occurs between 40 and 60 days after sowing (Bhyan et al. 2004). Effective weed management during this period is therefore essential to minimize yield losses and maintain crop productivity.

Chemical weed management remains the most practical and economical approach for controlling weeds in vegetable pea. Pendimethalin is widely used as a PE herbicide because of its effectiveness against annual grasses and certain broad-leaved weeds (BLWs) (Kulshrestha et al. 2000). However, its residual activity is often insufficient to suppress later-emerging weed flushes, necessitating supplementary PoE weed control (Kumar et al. 2022; Saikia et al. 2025). Imazethapyr has been reported to provide effective PoE control of several broad-leaved and grassy weeds in legumes and has improved weed management when applied sequentially after pendimethalin (Mawaliala et al. 2016; Rana et al. 2019; Singh et al. 2020). Nevertheless, sequential herbicide application in vegetable pea has already been extensively investigated, and the major challenge is no longer herbicide selection but improving the efficiency and precision of herbicide delivery.

Conventional post-emergence spraying often results in non-uniform herbicide deposition, spray drift onto crop foliage, and reduced herbicide-use efficiency, particularly in closely spaced legume crops. These limitations may reduce weed control effectiveness and increase the risk of crop injury, while repeated herbicide use also raises concerns regarding environmental contamination and herbicide resistance (Mortensen et al. 2012). Therefore, improving the method of herbicide application is becoming increasingly important for sustainable weed management.

Precision herbicide application technologies offer an opportunity to overcome these limitations by delivering herbicides directly to the target zone while minimizing off-target deposition. Among these technologies, **inter-row herbicide applicators (IRHAs)** enable precise placement of PoE herbicides between crop rows, thereby reducing unnecessary crop exposure and improving herbicide application efficiency. Despite their potential, information regarding the use of IRHAs for sequential herbicide application in vegetable pea remains limited, particularly under the agro-climatic conditions of the Indo-Gangetic Plains.

Therefore, the present study was undertaken to evaluate a **precision inter-row herbicide applicator (IRHA)** for PoE application of imazethapyr following pre-emergence pendimethalin in vegetable pea. The study aimed to determine whether precision herbicide application could improve weed management, crop performance, and economic returns compared with conventional post-emergence spraying methods.

2. MATERIALS AND METHODS

2.1 Experimental design

A two-year field experiment was conducted during the *rabi* seasons of **2023–24** and **2024–25** at the Agronomic Research Farm of Ranjeet Singh Memorial (P.G.) College, Dhampur, Bijnor, Uttar Pradesh, India. The study was undertaken to evaluate the effectiveness of different post-emergence (PoE) imazethapyr application methods, including a **precision inter-row herbicide applicator (IRHA)**, for weed management in vegetable pea. The experimental site is located at **29.021° N latitude and 78.508° E longitude**, at an elevation of **286 m above mean sea level (MSL)**. The soil at the experimental site was **silty loam** in texture, with a pH of **7.26** (slightly alkaline) and **0.36% organic carbon**.

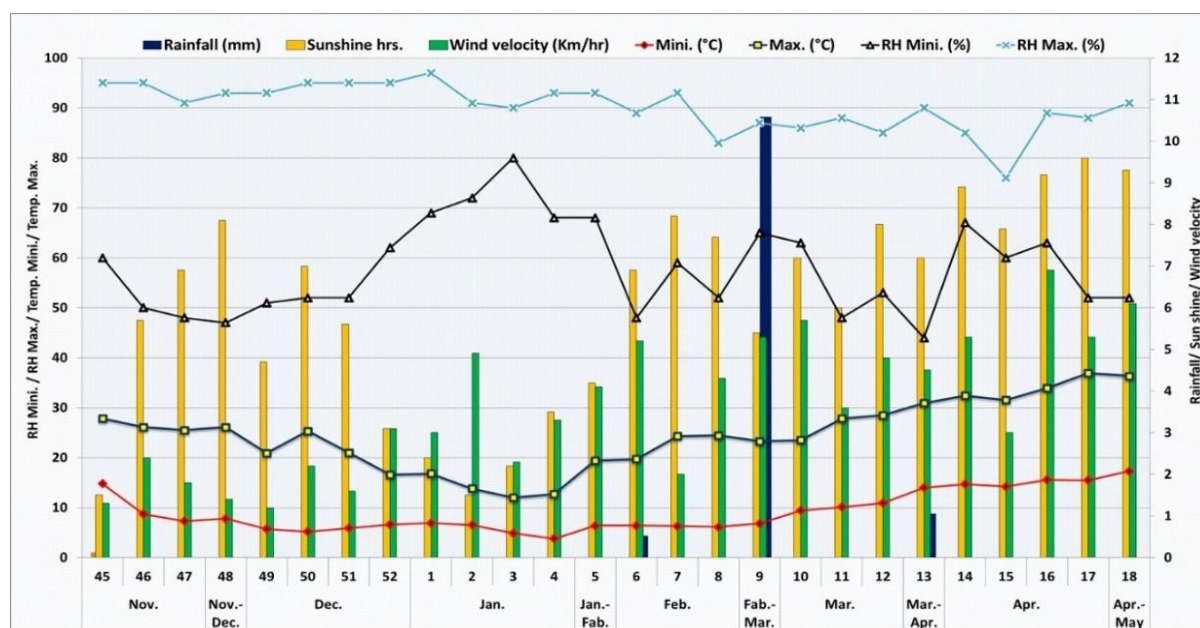


Fig. 2 Meteorological observations such as temperature, rainfall, and relative humidity were monitored throughout the first-year cropping season (2023–24).

The experiment was laid out in a **Randomized Complete Block Design (RCBD)** with **seven treatments** and **three replications** (Table 1).

Table 1. Particulars of treatments with their symbols

S. No.	Treatment	Symbol
1.	Spray of Pendimethalin	T ₁
2.	T ₁ fb spray of imazethapyr through a conventional sprayer (without protection)	T ₂
3.	T ₁ fb spray of imazethapyr through a spray hood	T ₃
4.	T ₁ fb spray of imazethapyr through the IRHA developed by R.S.M. (P.G.) College, Dhampur	T ₄
5.	HW at 15 and 30 DAS	T ₅
6.	Weed free	T ₆
7.	Weedy check (control)	T ₇

Note: Pendimethalin was applied as a pre-emergence (PE) herbicide at 1.0 kg a.i. ha⁻¹, whereas imazethapyr was applied as a post-emergence (PoE) herbicide at 60 g a.i. ha⁻¹, HW = Hand weeding, DAS = Days after sowing; fb = followed by; IRHA = Inter-Row Herbicide Applicator

A uniform basal fertilizer dose of **20–60–40 kg N–P₂O₅–K₂O ha⁻¹** was applied to all treatments before sowing. Vegetable pea cultivar **Azad Pea (C-10)** was sown on **11th December 2023** during the first season and **7th December 2024** during the second season. Seeds were manually sown in open furrows, which were subsequently covered with soil after seed placement.

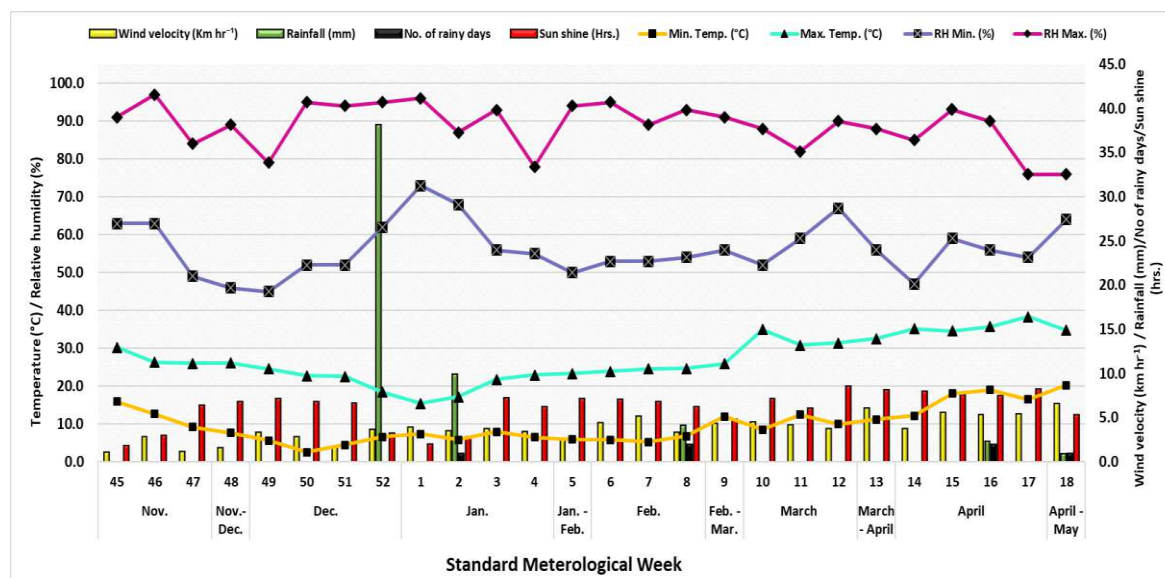


Fig. 3 Meteorological observations such as temperature, rainfall, and relative humidity were monitored throughout the second-year cropping season (2024–25).

2.2. Inter-row Herbicide Applicator (IRHA)

A precision Inter-row Herbicide Applicator (IRHA) was designed and developed at **Ranjeet Singh Memorial (P.G.) College, Dhampur, Uttar Pradesh, India**, to facilitate the selective PoE application of herbicides in pulse crops, particularly vegetable pea. Pulse crops are highly susceptible to herbicide injury during PoE application because of their close row spacing and the limited availability of selective herbicides. Moreover, conventional broadcast spraying often results in herbicide deposition on crop foliage, increasing the risk of phytotoxicity and reducing application efficiency. To address these limitations, the IRHA was developed to deliver herbicides precisely to the inter-row weed zone while minimizing spray contact with the crop canopy.

The IRHA consists of a rectangular metallic chamber mounted on four freely rotating wheels, enabling smooth movement between crop rows. The chamber is enclosed on the top and all four sides, whereas the bottom remains open to allow herbicide spray to reach only the weeds growing in the inter-row space. A connector is provided at the centre of the top cover, through which the spray lance of a conventional knapsack sprayer is attached. The spray nozzle is positioned inside the enclosed chamber, ensuring that the herbicide is discharged only beneath the cover (Fig. 4). During operation, the applicator is manually pushed along the crop rows at a uniform speed, allowing precise herbicide placement directly onto the target weeds while preventing spray drift onto adjacent crop plants.

The enclosed design of the IRHA substantially reduces off-target herbicide deposition and improves herbicide placement accuracy compared with conventional PoE spraying. The four-wheel support system maintains a uniform operating height throughout field operation,

thereby ensuring consistent spray coverage within the inter-row space. Consequently, the applicator enhances herbicide use efficiency, improves weed control, and minimizes the possibility of crop injury, making it particularly suitable for PoE weed management in pulse crops.

In the present study, the IRHA was used for the PoE application of imazethapyr at 60 g a.i. ha⁻¹ in Treatment T₄, while the remaining herbicide treatments were applied using their respective conventional application methods.

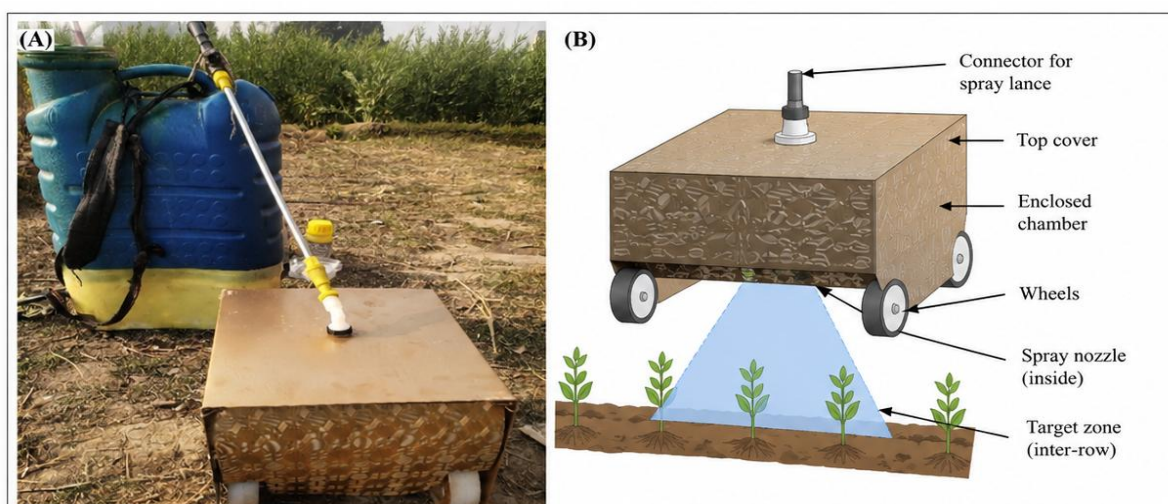


Fig. 4 Precision Inter-row Herbicide Applicator (IRHA) developed at Ranjeet Singh Memorial (P.G.) College, Dhampur, Uttar Pradesh, India, for selective PoE herbicide application in pulse crops. (A) Field photograph of the IRHA connected to a knapsack sprayer through a top-mounted connector. (B) Schematic representation showing the enclosed spray chamber, four-wheel support system, internal spray nozzle, and targeted herbicide application within the inter-row weed zone.

2.3 Data collection

Crop growth, weed parameters, yield attributes, yield, and economic data were recorded during both cropping seasons to evaluate the effectiveness of different PoE herbicide application methods. Weed density was determined using a **1.0 m² iron quadrat** placed randomly at representative locations within each net plot, and the dominant weed species were identified and classified into **broad-leaved weeds (BLWs)** and grassy weeds. Weed biomass was recorded after drying the weed samples to constant weight.

Crop observations were recorded at **20, 40, and 60 days after sowing (DAS)**, while yield attributes and yield were measured at crop maturity following standard agronomic procedures.

2.4 Statistical analysis

Data on weed parameters, crop growth, yield attributes, yield, and economics were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) using the Statistical Tool for Agricultural Research (STAR) version 2.0.1, developed by the International Rice Research Institute (IRRI), Los Baños, Philippines. When

treatment effects were significant, mean separation was performed using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level ($P \leq 0.05$).



View of experimental site



Inter row herbicide applicator

3. Computations of weed indices

3.1 Weed control efficiency (WCE, %)

Weed control efficiency (WCE) was calculated to evaluate the effectiveness of different weed management treatments in reducing weed density compared with the untreated (weedy check) control. WCE was calculated using the following equation:

$$WCE = \frac{WPC - WPT}{WPC} \times 100$$

Where,

WCE = Weed control efficiency (%)

WPC = Weed population (or density) in the untreated control plot

WPT = Weed population (or density) in the respective treated plot

3.2 Weed index (WI, %)

The weed index (WI) was calculated to estimate the reduction in crop yield under different weed management treatments relative to the weed-free treatment, following the method described by Gill and Kumar, (1969).

$$WI = \frac{Y_{wf} - Y_t}{Y_{wf}} \times 100$$

Where,

Y_{wf} = Yield obtained from the weed-free plot ($t\ ha^{-1}$)

Y_t = Yield recorded under the respective treatment plot ($t\ ha^{-1}$)

4. Results

4.1. Result on weed

4.1. Result on weed flora distribution

Table 2 Distribution of weed flora of vegetable pea as influenced by herbicide and PoE herbicide applicator devise

S.no	Weed species	Population m^{-2}	Percentage
1	<i>Avena fatua</i>	1.38	13.82
2	<i>Lepidium didymum</i> L.	1.76	17.64
3	<i>Coronopus didymus</i> L.	1.46	14.59
4	<i>Medicago arabica</i>	1.91	19.16
5	<i>Cynodon dactylon</i>	1.95	19.54
6	<i>Phalaris minor</i>	1.52	15.25
Total		9.99	100.00

The Table 2 shows that *Cynodon dactylon* and *Medicago arabica* were the dominant weeds respectively, accounting for 19.54% and 19.16% of the total weed flora.

4.1.1 Weed index

As illustrated in Fig. 5 (a), the lowest weed index was noted in the weed-free treatment (T_6); statistically, it was at par with T_1 fb Spray Imazethapyr through IRHA (T_4) and HW @ 15 and 30 DAS (T_5). These treatments were significantly superior to the remaining treatments. In contrast, the weedy check (control) (T_7) noted the highest weed index.

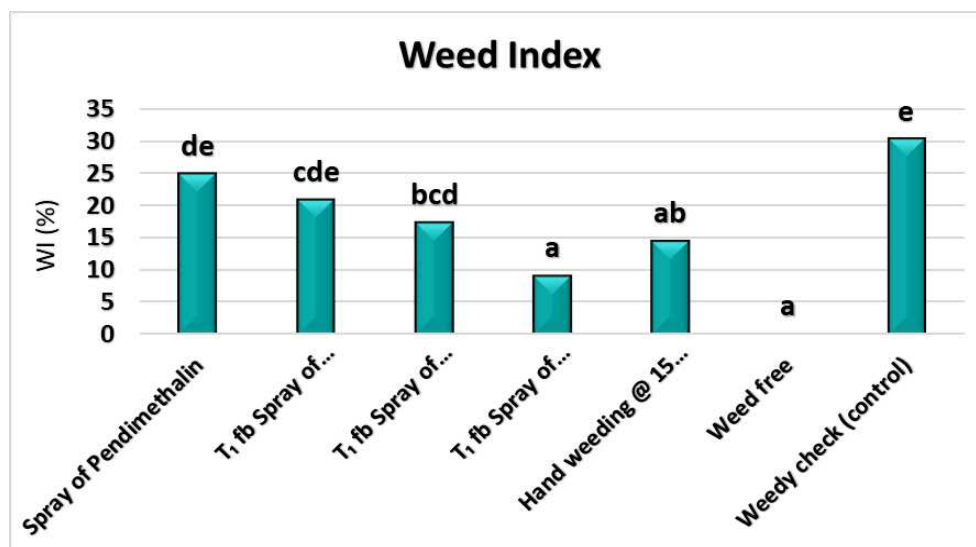


Fig. 5 (a)

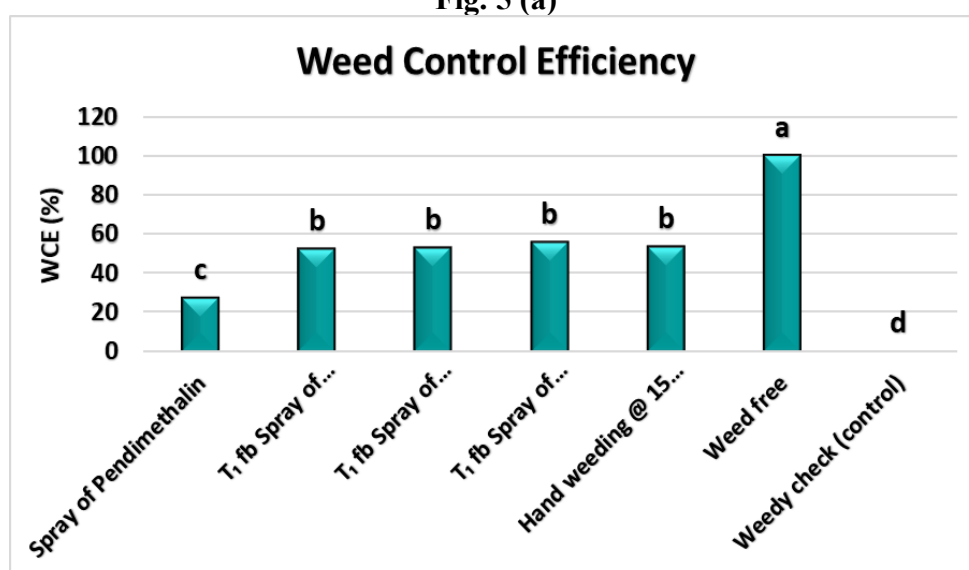


Fig. 5 (b)

The data on WI and WCE as influenced via different treatments are presented in graphically illustrated in Fig. 5 (a–b)

4.1.2 Weed control efficiency (WCE)

The results presented in Fig. 5 (b) that weed – free treatment (T_6) significantly surpassed the other treatments in terms of WCE. Among the herbicide-based treatments, T_1 fb Spray Imazethapyr through IRHA (T_4) reported highest WCE which was significantly superior to spray of Pendimethalin (T_1) and weedy check (control) (T_7) treatments and statistically at par with the remaining treatments.

4.2. Result on Pre – Harvest parameters

The weed-free treatment (T₆) recorded the maximum plant height [(Fig. 6 (a))] throughout both years of the study. Among the herbicidal treatments, T₁ *fb* Spray Imazethapyr through IRHA (T₄) produced the tallest plants, which were statistically comparable to the other treatment. In distinction, the weedy check (T₇) observed the minimum plant height.

The weed free treatment (T₆) also produced the maximum number of branches plant⁻¹, *fb* T₄ (T₁ *fb* Spray Imazethapyr through IRHA), indicating the positive result of effective weed management on improving crop growth and yield attributes [(Fig.6 (b))].

Observations on vegetative growth were occupied to evaluate the selectivity and effectiveness of PoE imazethapyr applied through different applicator devices. Among all treatments, the weed free plot (T₆) produced the maximum number of leaves [(Fig.6 (c))]. Among herbicidal treatments, T₁ *fb* Spray Imazethapyr through IRHA (T₄) recorded comparatively higher leaf numbers. In contrast, severe weed infestation in T₇ resulted in the lowest number of leaves. A similar trend was observed for leaf area throughout both years of the trials [(Fig.6 (d))].

Data on plant fresh weight, as influenced by herbicide treatments and applicator devices, are illustrated in [(Fig.6 (e))]. The treatment weed free (T₆) noted the highest plant fresh weight, which was significantly excel over to the remaining treatments. Among the herbicidal treatments, T₁ *fb* Spray Imazethapyr through IRHA (T₄) was proved to be the most effective and recorded significantly higher plant fresh weight which was superior to weedy check (T₇) and it observed the lowest plant fresh weight throughout both years of the study.

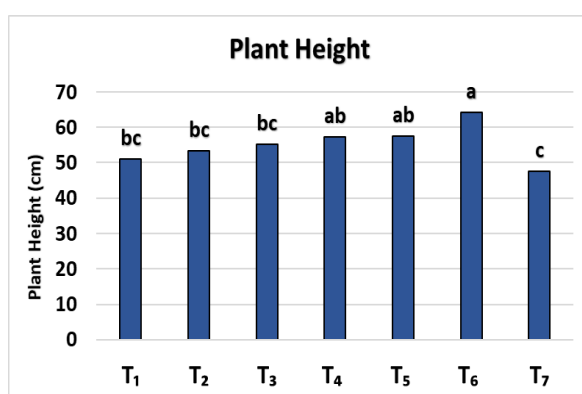


Fig. 6 (a)

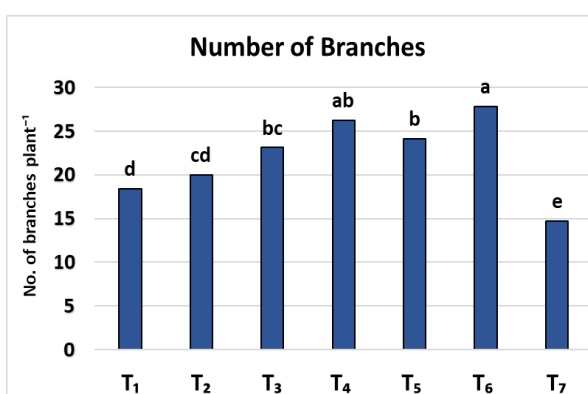


Fig. 6 (b)

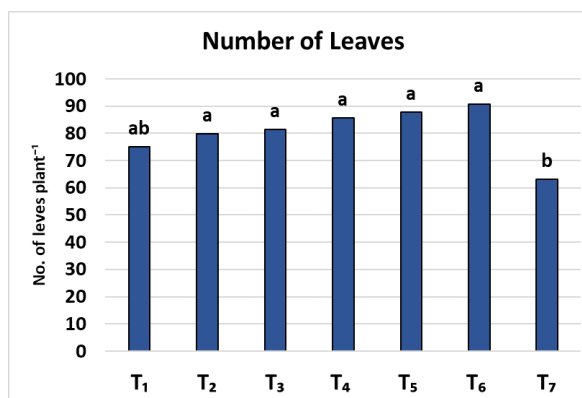


Fig. 6 (c)

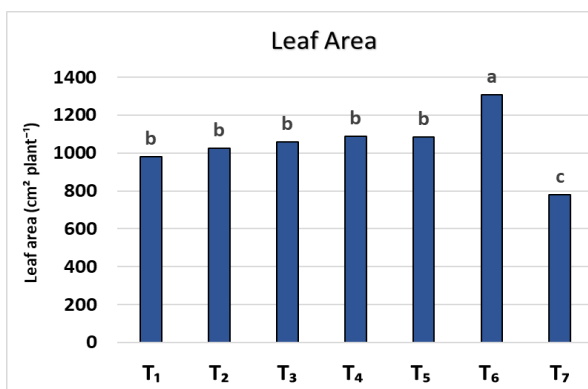


Fig. 6 (d)

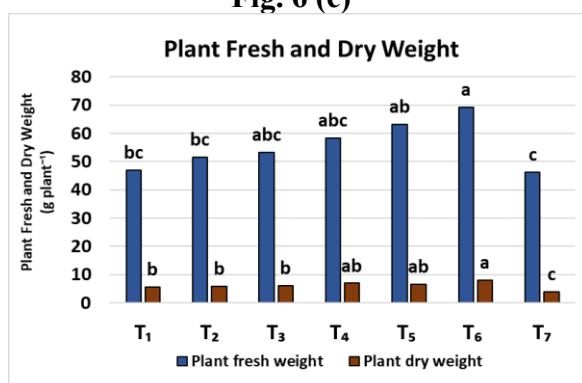


Fig. 6 (e)

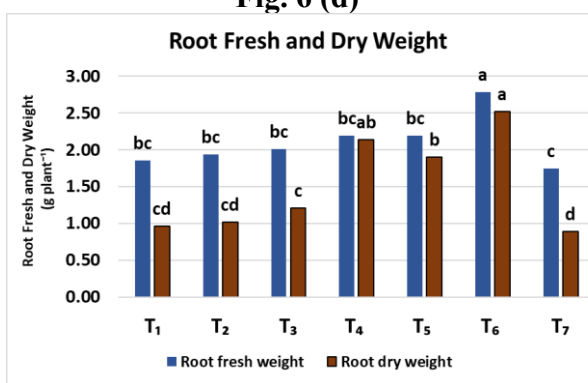


Fig. 6 (f)

Data pertaining to pre-harvest and root characteristics under various treatment combinations are summarized and depicted in Fig. 6 (a–f).

A parallel tendency was observed for plant dry weight shown in [(Fig. 6 (e))]. The weed free treatment (T₆) noted the higher plant dry weight, while the weedy check (T₇) resulted in the minimum dry weight. Among the herbicidal treatments, T₄ (T₁ fb Spray Imazethapyr through IRHA) recorded significantly higher plant dry weight than the remaining treatments and at par with treatment HW at 15 and 30 DAS (T₅), indicating the positive consequence of effective weed management on plant growth.

4.3 Result on root parameters

Data on root fresh weight are graphically illustrated in [(Fig. 6 (f))], depicting the effect of different treatments at various observation intervals. Root fresh weight increased progressively with crop growth. Across together years of trials, the weed free treatment (T₆) recorded the highest fresh root weight at all stages of plant. The application of T₁ fb Spray of Imazethapyr through IRHA (T₄) produced a high fresh root weight among the herbicide treatments; this was equivalent to the other herbicide treatments and much greater than the weedy check (T₇). Similarly, the highest root dry weight [(Fig.6 (f))], was recorded under the weed free treatment (T₆). Among the herbicidal treatments, T₁ fb Spray Imazethapyr through

IRHA (T₄) also recorded significantly higher root dry weight compared to the remaining herbicidal treatments.

4.4 Result on yield attributes and yields

Data on pod length as inclined by different weed management treatments are illustrated in Fig. 7 (a). The consequences revealed that the weed free treatment (T₆) noted the maximum pod length, which was significantly superior to treatments T₁, T₂ and T₇ and identical to other treatment. Among the herbicidal treatments, T₁ *fb* Spray of Imazethapyr through IRHA (T₄) recorded higher pod length and was significantly better than herbicidal T₁ and T₇ treatments during both years.

The data presented in Fig. 7(b) also indicated that the highest number of pods plant⁻¹ was obtained in the weed free treatment (T₆). Statistically, this was on par with T₁ *fb* Spray of Imazethapyr through IRHA (T₄) but significantly excel over to the other treatments. The minimum number of pods remained detected in the weedy check (T₇). But among the herbicidal treatment T₄ (T₁ *fb* Spray of Imazethapyr through IRHA) was significantly superior from T₁ and T₇ and at pat with remaining treatment.

Data on number of seeds pod⁻¹ under various weed management treatments are presented in Fig. 7 (c). The outcomes showed that the weed – free treatment (T₆) produced the maximum number of green seeds pod⁻¹, *fb* T₄ (T₁ *fb* Spray of Imazethapyr through IRHA), which was at par to the remaining herbicidal treatments and lowermost number of number of seeds plant⁻¹ was recorded under the weedy check (T₇) for both years of study.

Similarly, the highest single pod weight was noted under the weed – free treatment (T₆), which was excel over from all the remaining treatments. Amongst the herbicidal treatments T₄ (T₁ *fb* Spray of Imazethapyr through IRHA) which endured statistically at par with T₃ and T₅, whereas the weedy check (T₇) recorded the lowest value Fig. 7 (d).

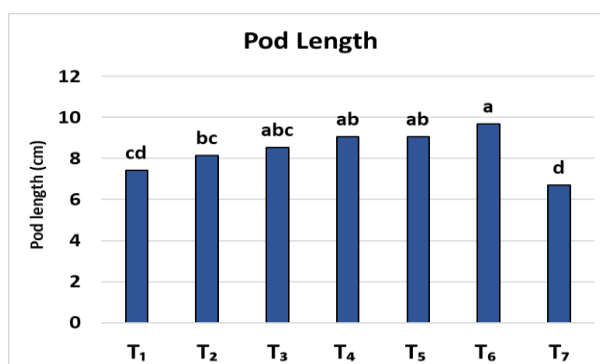


Fig. 7 (a)

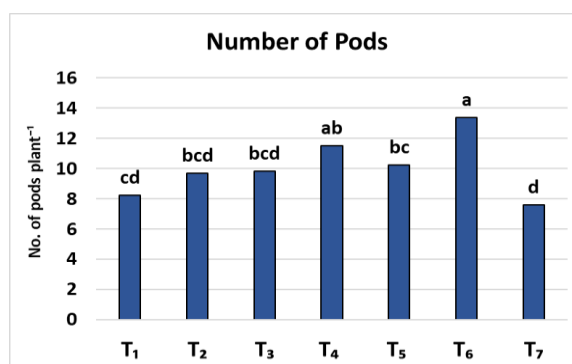
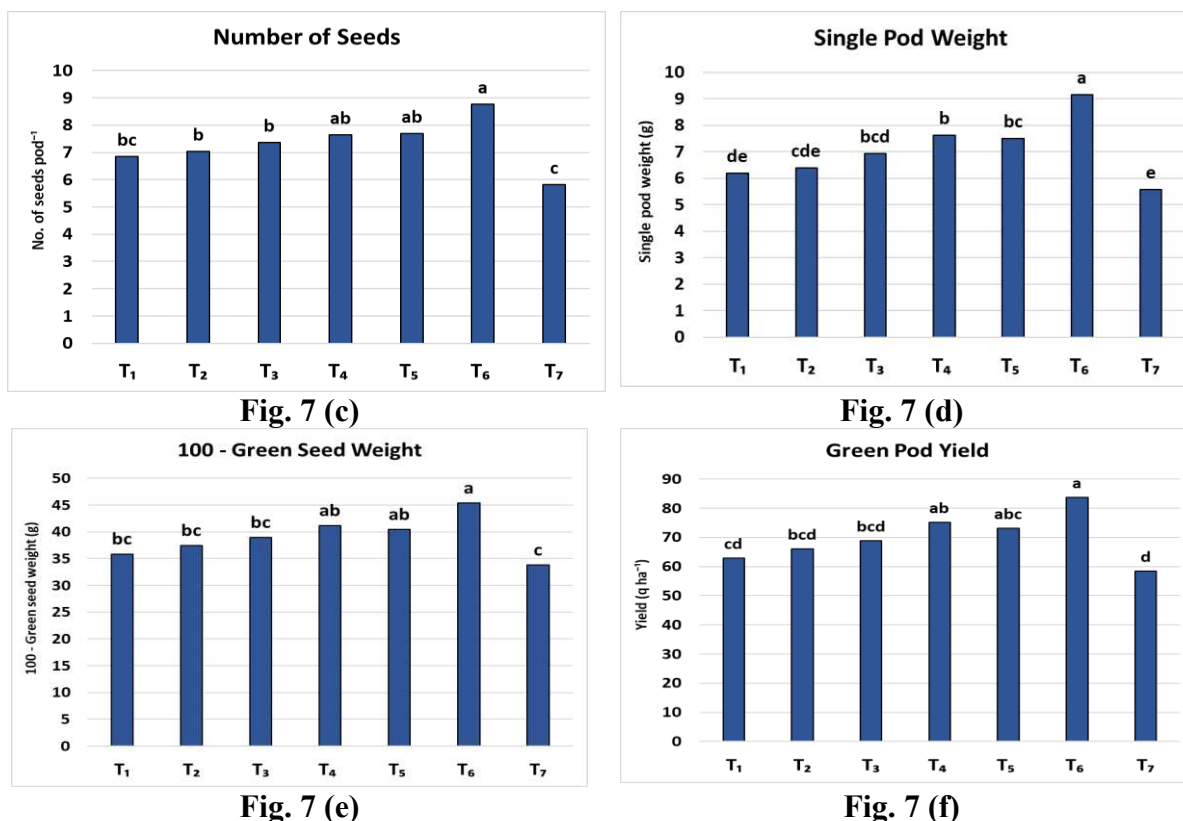


Fig. 7 (b)



Data pertaining to yield parameters under various treatment combinations are summarized and depicted in Fig. 7 (a–f).

A thorough analysis of the data revealed that the weed free treatment (T₆) [(Fig. 7(e)] had the highest weight of 100 green seeds; this was statistically identical to T₄ (T₁ fb Spray of Imazethapyr through IRHA) and T₅ (HW at 15 and 30 DAS), but it significantly surpassed the other treatments. However, across the treatment combinations herbicide treatments, T₄ (T₁ fb Spray of Imazethapyr through IRHA) was significantly superior to T₇ (weedy check) and comparable to the other treatments.

The highest total green pod yield Fig. 7 (f) was recorded under the weed free treatment (T₆) which was at par with T₄ (T₁ fb Spray of Imazethapyr through IRHA) and T₅ (HW at 15 and 30 DAS), but significantly superior than the other treatments. The least green pod yield was observed under the weedy check (T₇). Next best treatment was T₄ (T₁ fb Spray of Imazethapyr through IRHA) which significantly superior to T₁ and T₇.

4.5 Result on economics

For vegetable peas, the weed free (T₆) approach exhibited the highest cultivation costs, whereas the weedy check (control) (T₇) had the lowest cultivation costs, as illustrated in Fig. 8(a).

According to the statistics, the weed free treatment (T₆), *fb* T₄ (T₁ *fb* Spray of Imazethapyr through IRHA), and Fig. 8(b) exhibited the highest gross return.

Similarly, the maximum net return [Fig. 8 (c)] was obtained underneath the weed – free treatment (T₆), which was identical with T₁ *fb* Spray of Imazethapyr through IRHA (T₄), but significantly higher than the remaining treatments. The next best treatment was T₁ *fb* Spray of Imazethapyr through IRHA (T₄) which was superior from T₁, T₂ and T₇ but at par with the remaining treatment. The lowest gross return was recorded under the weedy check (T₇).

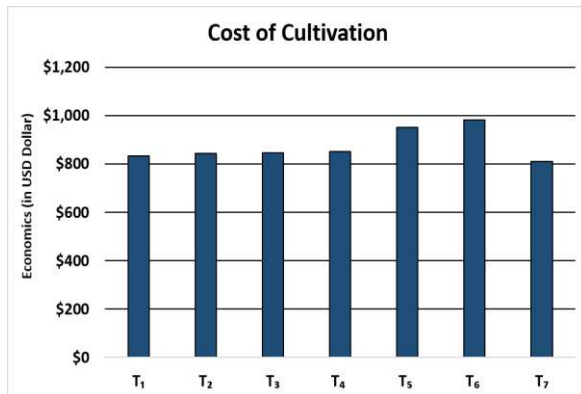


Fig. 8 (a)

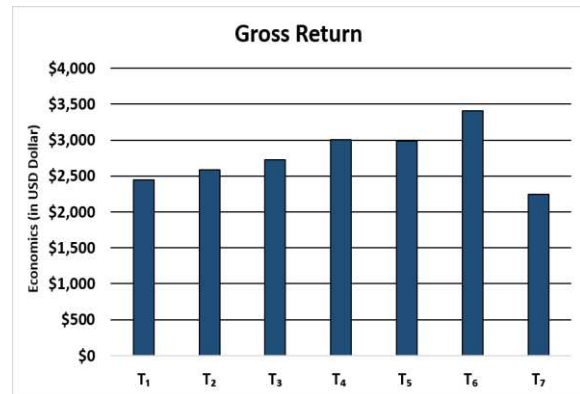


Fig. 8 (b)

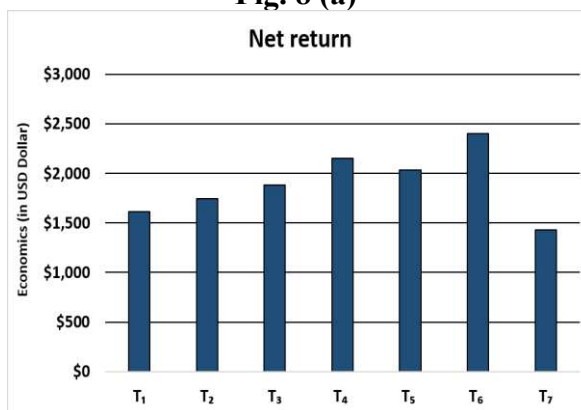


Fig. 8 (c)

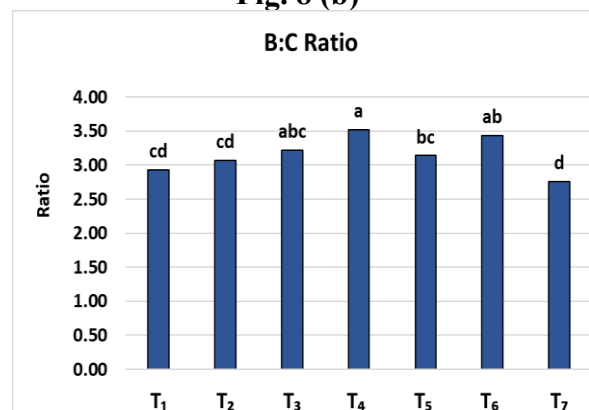


Fig. 8 (d)

Fig. 8 (a–d) provides a graphic representation of the data on economics as inclined by various treatments.

With respect to the benefit–cost ratio (BCR) [Fig. 8 (d)], the highest BCR was recorded underneath the weed free treatment (T₆), which was significantly higher from T₁, T₂, T₅ and T₇ than the other treatments. Amongst the herbicidal treatments, T₄ (T₁ *fb* Spray of Imazethapyr through IRHA) recorded the highest BCR. The lowest BCR was observed under the weedy check (control) (T₇).

5. DISCUSSION

5.1 Effect of herbicides and the inter-row herbicide applicator on weed parameters

5.1.1 Distribution of weed flora

The experimental field was infested with a diverse weed flora comprising both grassy and broad-leaved weeds (BLWs) (Table 2). Among the identified species, *Cynodon dactylon* (19.54%) and *Medicago arabica* (19.16%) were the most dominant, *fb* *Lepidium didymum* (17.64%), *Phalaris minor* (15.25%), *Coronopus didymus* (14.59%), and *Avena fatua* (13.82%). The predominance of *C. dactylon* agrees with the findings of Bazaya *et al.* (2023); Das *et al.* (2024); Kashyap *et al.* (2022); Sethi *et al.* (2021); Shiv *et al.* (2023); Singh, (2003), who also reported this species as one of the dominant weeds in pea and chickpea under North Indian conditions.

Similarly, the substantial occurrence of *P. minor* in the present study is consistent with earlier reports by Bazaya *et al.* (2023); Das *et al.* (2024); Hetta *et al.* (2022); Mawalia *et al.* (2016); Rana *et al.* (2019); Singh and Angiras, (2004), who identified it as a major grassy weed in pea fields. The abundance of *C. didymus* also agrees with the observations of Kaur *et al.* (2023); Kumar and Singh, (2024); Singh *et al.* (2015); Singh and Angiras, (2004).

Likewise, the occurrence of *A. fatua*, *L. didymum*, and *M. arabica* is in accordance with previous studies conducted in pea and other winter legumes (Mawalia *et al.* 2016; Rana *et al.* 2019; Bazaya *et al.* 2023; Das *et al.* 2024; Meleta *et al.* 2024). Differences in weed flora reported among studies may be attributed to variations in soil characteristics, climatic conditions, cropping history, irrigation practices, and weed management strategies. Earlier studies have identified *Chenopodium album*, *Anagallis arvensis*, *Fumaria parviflora*, and *Vicia* spp. as dominant weeds in pea (Singh 2003; Thamburaj and Singh 2013; Hetta *et al.* 2022; Gairola *et al.* 2024; Nagar *et al.* 2025). Their relatively lower abundance in the present study highlights the location-specific nature of weed flora.

5.1.2 Weed control efficiency (WCE)

The weed-free treatment (T₆) recorded the highest weed control efficiency throughout the crop growth period because complete weed removal eliminated crop–weed competition. Although this treatment provided the greatest level of weed suppression, maintaining weed-free conditions through manual weeding is labour-intensive and economically impractical under commercial farming conditions.

Among the herbicide-based treatments, T₁ *fb* Spray Imazethapyr through IRHA (T₄) consistently recorded the highest weed control efficiency. The superior performance of this treatment can be attributed not only to the sequential herbicide programme but also to the precision application achieved by the IRHA. The enclosed design of the applicator directed the herbicide specifically to the inter-row zone, thereby improving herbicide deposition on target weeds while minimizing spray drift onto the crop canopy. This precise placement enhanced weed suppression throughout the growing season without increasing crop injury.

The effectiveness of sequential herbicide application observed in the present study agrees with previous reports by Barla and Upasani, (2021); Das, (2016); Kumar *et al.*, (2019); Mawalia *et al.* (2016); Nagar *et al.* (2025); Shiv *et al.*, (2023); Singh *et al.* (2021); Yadav *et al.* (2019), who reported that pendimethalin *fb* imazethapyr effectively reduced weed density and biomass in pea and chickpea. However, the present investigation further demonstrates that improving the **method of herbicide application** through the IRHA can substantially enhance weed control compared with conventional PoE spraying by improving application accuracy and reducing off-target herbicide losses.

5.1.3 Weed index (WI)

The T₁ *fb* Spray Imazethapyr through IRHA (T₄) recorded the lowest weed index among all herbicide treatments, whereas the weedy check (T₇) produced the highest weed index because of severe crop–weed competition throughout the growing period. The lower weed index observed under T₄ reflects its superior weed suppression and the resulting reduction in yield losses.

The improved performance of T₄ can be attributed to the complementary activity of the two herbicides together with the precision application achieved by the IRHA. Pendimethalin effectively suppressed the initial flush of weeds, whereas imazethapyr controlled later-emerging grassy and broad-leaved weeds. Application through the IRHA ensured accurate herbicide placement within the inter-row space while minimizing contact with the crop canopy, thereby reducing crop injury and maintaining crop growth. Consequently, crop resources such as light, nutrients, moisture, and space remained more available for the crop, resulting in improved yield and a lower weed index.

These findings are consistent with those of Barla and Upasani, (2021); Das, (2016); Girish *et al.* (2024); Kumar *et al.* (2019); Mawalia *et al.* (2016); Nagar *et al.* (2025); Sanketh *et al.* (2021); Shiv *et al.* (2023); Singh *et al.* (2021); Yadav *et al.* (2019), who reported improved weed control and reduced yield losses following sequential application of pendimethalin and imazethapyr in legume crops. The present study extends these findings by demonstrating that **precision inter-row herbicide application** can further improve the effectiveness of post-emergence weed management while enhancing crop safety, thereby reducing yield losses more effectively than conventional application methods.

5.2 Effect of herbicides and the inter-row herbicide applicator on crop growth parameters

The weed-free treatment (T₆) produced the highest values for all crop growth parameters, including plant height, number of leaves plant⁻¹, leaf area, number of branches plant⁻¹, and fresh and dry biomass. The superior growth observed under this treatment can be attributed to the complete elimination of crop–weed competition throughout the growing season, which ensured uninterrupted availability of essential resources such as light, water, nutrients, and growing space. Consequently, the crop achieved greater vegetative growth and biomass accumulation. Similar improvements in plant growth under effective weed management have been reported by Rana *et al.* (2001).

Among the herbicide-based treatments, sequential application of T₁ *fb* Spray Imazethapyr through IRHA (T₄) consistently produced superior growth attributes and ranked next to the weed-free treatment. The improved crop performance was not only due to effective season-long weed suppression but also to the precision application achieved by the IRHA. Unlike conventional spraying, the enclosed design of the applicator directed the herbicide specifically to the inter-row space, thereby minimizing spray drift and reducing herbicide deposition on the crop canopy. This reduced the risk of herbicide-induced phytotoxicity while maintaining effective weed control, allowing the crop to utilize available resources more efficiently for vegetative growth.

Previous studies have shown that sequential application of pendimethalin and imazethapyr effectively improves crop growth by reducing weed competition (Yadav *et al.* 2019; Gairola *et al.* 2024). Likewise, Pendimethalin provides effective control of grassy weeds,

whereas imazethapyr controls a broad spectrum of broad-leaved and grassy weeds (Singh et al. 2021; Nagar et al. 2025). However, the efficiency of PoE herbicides depends greatly on the method of application. Thakur *et al.* (2024) reported that improper application or excessive herbicide deposition may suppress crop growth because of phytotoxic effects. The findings of the present study support this observation by demonstrating that precise inter-row application through the IRHA minimized crop exposure to imazethapyr while maintaining effective weed control.

The present findings are further supported by Barla and Upasani, (2021); Sanketh *et al.* (2021), who reported that sequential herbicide application combined with precise or mechanical weed management significantly reduced weed biomass and improved crop growth in legumes. The present study extends these findings by demonstrating that precision inter-row herbicide application can further enhance crop growth by improving herbicide placement and reducing off-target deposition.

Overall, although the weed-free treatment (T₆) achieved the greatest vegetative growth, the T₁ *fb* Spray Imazethapyr through IRHA (T₄) emerged as the most practical and effective weed management strategy. The IRHA combined efficient weed suppression with reduced crop injury, resulting in greater plant growth and biomass accumulation under field conditions.

5.5 Effect of herbicides and the inter-row herbicide applicator on economics

The economic analysis demonstrated that the weed-free treatment (T₆) recorded the highest gross return, net return, and benefit–cost (B:C) ratio because complete weed control maximized crop growth and green pod yield. However, maintaining a weed-free crop through manual weeding is labour-intensive and costly, making it less practical under commercial production systems.

Among the herbicide-based treatments, sequential application of T₁ *fb* Spray Imazethapyr through IRHA (T₄) generated the highest gross return, net return, and B:C ratio. The superior economic performance of T₁ *fb* Spray Imazethapyr through IRHA (T₄) was primarily attributed to its ability to provide effective weed control while minimizing crop injury through precision herbicide application. The enclosed design of the IRHA reduced spray drift onto the crop canopy, thereby lowering the risk of herbicide-induced phytotoxicity and maintaining optimum crop growth and productivity. Consequently, higher green pod yield compensated for the cost of herbicide application, resulting in greater economic returns than the other herbicide application methods.

The present findings are consistent with those of Chaubey *et al.* (2016); Mathukia *et al.* (2015); Mawalia *et al.* (2016); Yadav *et al.* (2019), who reported that sequential herbicide application improved profitability by enhancing weed control and crop yield in pea and chickpea. Similar improvements in net returns and benefit–cost ratio following sequential herbicide programmes have also been reported by Bazaya *et al.* (2023); Gairola *et al.* (2024); Girish *et al.* (2024); Kashyap *et al.* (2022); Kumar and Singh, (2024); Nagar *et al.* (2025); Rastogi *et al.* (2021); Sethi *et al.* (2021); Singh *et al.* (2021); Thakur *et al.* (2024)

While previous studies have demonstrated the economic benefits of sequential herbicide programmes, the present study further indicates that **precision herbicide application can substantially improve profitability**. By enhancing herbicide placement, reducing off-target losses, and minimizing crop injury, the IRHA increased herbicide use efficiency and

improved crop productivity without increasing weed management costs. These advantages translated into higher economic returns compared with conventional post-emergence herbicide application.

Overall, although the weed-free treatment (T₆) achieved the highest economic returns, the sequential application of T₁ *fb* Spray Imazethapyr through IRHA (T₄) emerged as the most practical and economically viable weed management strategy. The combination of effective weed suppression, improved crop safety, enhanced productivity, and greater profitability demonstrates the potential of the IRHA as a precision weed management technology for sustainable vegetable pea production.

6. Conclusion

The present study demonstrated that effective weed management markedly improved weed suppression, crop growth, green pod yield, and economic returns in vegetable pea. Although the weed-free treatment (T₆) achieved the highest overall performance, it is labour-intensive and less practical under commercial production conditions.

Among the herbicide-based treatments, sequential application of T₁ *fb* Spray Imazethapyr through IRHA (T₄) proved to be the most effective. This treatment provided season-long weed suppression, reduced weed density and weed biomass, minimized crop injury through precision inter-row herbicide application, and consequently improved crop growth, yield attributes, green pod yield, and economic returns.

The findings demonstrate that the **IRHA enables precise post-emergence herbicide placement**, thereby improving herbicide use efficiency while reducing off-target deposition on the crop canopy. This precision application approach offers a practical and economically viable alternative to conventional post-emergence herbicide spraying in vegetable pea.

Overall, sequential application of pendimethalin followed by imazethapyr through the **Inter-row Herbicide Applicator** can be recommended as an effective precision weed management strategy for vegetable pea cultivation under the agro-climatic conditions of the North-Western Plains Zone of Uttar Pradesh. The technology has considerable potential to improve crop safety, reduce labour requirements, and enhance farm profitability, making it a promising approach for sustainable pulse production.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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