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Sequential herbicide application coupled with mulch enhances the productivity and quality of winter onion (*Allium cepa* L.) while effectively controlling the mixed weed flora

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Weed control poses substantial difficulties for winter season onion (*Allium cepa* L.) cultivation in the north-western Indo-Gangetic Plains, primarily due to the constrained efficacy of the existing herbicides. To address this issue, a 2-year field study was conducted to assess the efficacy of pre- and post-emergence herbicides (pendimethalin, ethoxysulfuron, imazethapyr, and quizalofop-p-ethyl) individually and in combination with crop residue mulch for weed control in winter onion. The results revealed that using herbicides or mulches in isolation did not provide satisfactory weed control. However, the integration of natural mulch with pendimethalin followed by quizalofop-p-ethyl application proved to be the most effective weed control strategy, resulting in the least reduction in bulb yield (10.3%) compared to other treatments. On the contrary, combinations of pendimethalin with ethoxysulfuron or imazethapyr showed adverse effects on the onion crop and inflicted the highest yield losses among all treatments (78.6 and 83.4%, respectively). However, the combination of pendimethalin with quizalofop-p-ethyl coupled with crop mulch resulted in season-long weed control and over 80% bulb yield (36.58 t/ha) gains compared to the weed-free condition. These findings emphasize the efficacy of combining herbicides and mulches as an integrated weed management strategy for onions. By adopting such integrated approaches, farmers could improve weed control while maintaining bulb yield and quality, reducing the risks associated with herbicide resistance, and promoting sustainable onion production in the north-western Indo-Gangetic Plains.

KEYWORDS

organic mulch, pendimethalin, quizalofop-p-ethyl, weed management, winter onion quality

1 Introduction

Onion (*Allium cepa* L.) is one of the most essential vegetables and condiments that is frequently used in every household year-round (Gupta et al., 2020). After the tomato, it is regarded as the second most important vegetable; hence, it is referred to as "The Queen of the Kitchen". Both the onion bulbs and green leaves are excellent sources of minerals such as calcium, phosphorus, and vitamin C as well as carbohydrates and proteins (Rahman et al., 2013). Consuming onions is also known to reduce coronary heart disease and other illnesses (Sangha and Baring, 2003). It is an important export-oriented vegetable among the cultivated *Allium* sp. in India and contributes to ∼70% of the foreign exchange among fresh vegetables. China, India, the United States, Turkey, Japan, Iran, Pakistan, Spain, and Brazil are the major onion-producing nations (Paikra et al., 2022). Next to China, India is the world's second-largest producer of onions; however, India's productivity is quite poor (18.2 tons/ha), as compared to China and other nations like Egypt, the Netherlands, and Iran (DAC and FW, 2019–2020). In India, it is planted over an area of 1.43 million ha with an annual production of 26.15 million tons (DAC and FW, 2019–2020). The principal reason for low onion productivity is its long-duration cultivars (120–180 days), which suffer from successive weed flushes (Minz et al., 2018). Furthermore, reduced smothering effects attributed to the short stature of the onion plants, characterized by narrow, erect, and smaller leaf size, coupled with the slow early-stage vegetative growth of onions, result in significant competition from weeds. This competition primarily affects the crop's access to light and space, in addition to intensifying challenges related to nutrient and soil moisture availability (Dhananivetha et al., 2017). In general, weed infestation causes bulb yield losses of up to 40–80% (Ramalingam et al., 2013; Rathod et al., 2014; Vishnu et al., 2014), depending on the weed interference and cultural practices (Kaur et al., 2018). Losses caused by weeds have been estimated to be much higher than those caused by insects, pests, and diseases. In addition, numerous studies report bulb quality reduction due to stiff weed competition in the onion crop (Priya et al., 2017). Thus, weed management using appropriate methods and in a time-bound manner is crucial for proper bulb development and profitable onion production.

In many vegetable crops, mechanical weeding is relatively easier due to their wider spacing. However, onion crops present significant challenges for mechanical weeding due to their shallow rooting system and closer inter-row spaces, making weed control extremely difficult (Dhananivetha et al., 2017). Moreover, manual weeding is costly, time-consuming, and labor-intensive, making chemical control the major approach for weed control in onion fields. Unfortunately, the options for post-emergence herbicides in onion crops are limited, and the only widely advocated pre-emergence broad-spectrum herbicide is pendimethalin. However, due to the long-duration and slow initial growth of the onion crop, weeds that emerge at later stages of ontogeny, specifically after 20–25 days of transplanting, become difficult to control (Jat Priynka et al., 2018).

However, integrating cultural practices, such as crop residue mulching, with crop establishment methods, like sowing onions on narrow or broad beds, has been found to have highly beneficial effects in achieving improved and efficient weed control. Pendimethalin has been used and reported by various researchers as an effective weed control option in onions. However, for post-emergence applications, the problem lies in the undesirable outcome of phytotoxicity when applied (Uygur et al., 2010). Particularly in winter onions, the concerns are heightened by phytotoxicity and the potential carryover effects on subsequent crops. Since pendimethalin controls only early-season weed flushes, the use of post-emergence broad-spectrum herbicides such as ethoxysulfuron, quizalofop-p-ethyl, and imazethapyr has been tried and suggested by various researchers (APVMA, 2008; Liman et al., 2015; Hazra et al., 2023). However, there is a lack of information regarding the combined impact of pre- and post-emergence herbicide applications on *rabi* (winter) onion yield and quality. Additionally, no research data exist on the combined application of crop residue mulch, sowing of crops on beds, and sequential herbicidal treatments concerning onion quality parameters such as crop dry matter, total soluble solids, total phenols, flavonoids, ferric reducing antioxidant power (FRAP), cupric reducing antioxidant capacity (CUPRAC), and bulb yield. Incorporating cultural practices has shown promise in improving weed control, but more studies are needed to understand the combined effects of herbicide applications and crop residue mulching on onion yield and quality parameters. Such information could be instrumental in devising integrated and sustainable weed management strategies for onion cultivation.

Considering the research gaps and the need for efficient weed management, the present field study was planned and executed by choosing a combination of pre- and post-emergence herbicides in conjunction with different crop establishment systems and residue recycling options. We hypothesized that the effectiveness of herbicides increases in weed control under sequential applications coupled with residue mulching and crop establishment methods. Furthermore, the study was conducted to determine the effects of the pre- and post-emergence herbicidal application on important quality parameters of onion, mainly total phenols, flavonoids, and antioxidant contents.

2 Materials and methods

2.1 Experimental site and soil characteristics

A field experiment was conducted during the *rabi* (winter) seasons of 2016–17 and 2017–18 at ICAR-IARI, New Delhi, located at 28°38′ N latitude, 77°10′ E longitude, and 229 m altitude. The area has a semi-arid and subtropical climate with hot, dry summers and cold winters. During the crop period, a total rainfall of 165.3 mm in 2016–17 and 66.6 mm in 2017–18 was received. The distribution of important weather variables such as minimum and maximum temperatures and rainfall during both study years has been shown in Figure 1. The soil of the experimental site was sandy loam, low in organic C (0.43%) and available N (177.7 kg ha^{-1}) and medium in available P (11.6 kg ha^{-1}) and available K (178.5 kg ha^{-1}), with a pH of 7.6 and an EC of 0.33 dSm^{-1}. The topography of the site was even and well-drained. The irrigation was provided through the surface check basin method.

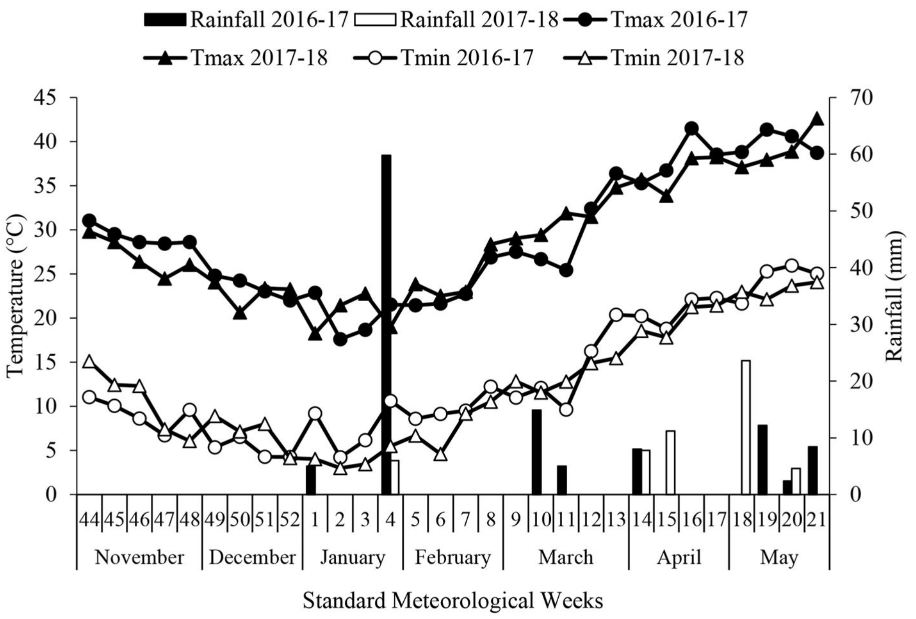

FIGURE 1
Rainfall (mm) and maximum and minimum temperatures (°C) during crop growing periods (November–May) in 2016–17 and 2017–18.

The investigation was executed employing a split-plot design, wherein three distinct crop establishment systems were allocated to the main plots, while six varied weed control treatments, encompassing both pre-emergence and post-emergence strategies, were assigned to the sub-plots (Table 1).

Pre-sowing irrigation was applied uniformly to the entire field. The field was plowed once by a tractor-drawn disk plow, followed by three harrowings for making soil pulverized with fine tilth. The soil was leveled by a soil leveler after each plowing. The winter onion variety "Pusa Ridhi" was transplanted on 15 January 2017 and 14 January 2018, with a planting geometry of 15 × 7.5 cm. The size of the main plot was 600 m^2 and the sub-plot size was 100 m^2, with three replications. In bed transplanting, three rows of onion seedlings were sown on a 60-cm wide bed top, leaving 7.5 cm on both sides of the bed and 15 cm between the rows. Irrigation was provided in 30 cm wide furrows in the bed-planting system of the establishment. All the recommended packages of practices were followed for raising a healthy crop.

At 60 days after transplant (DAT), a square sampling frame measuring 0.5 × 0.5 m was randomly positioned within each experimental plot. These plots consisted of three rows of onions, each spanning a length of 50 cm. The purpose of this sampling was to assess and quantify the weed population within the designated area. Weeds present within the sampling frame were precisely counted based on their respective species. After counting, the collected weeds were subjected to a 2-day sun-drying process, followed by placement in an oven set at 65 ± 5°C for an additional 48 h to record their dry weight. To evaluate the effectiveness of a particular treatment in comparison to a weed-free scenario, the weed index (WI) was computed using Equation (1). The weed index serves as a metric to gauge the impact of treatment on overall yield output, expressing the percentage of yield loss attributed to the applied treatment when contrasted with the weed-free control treatment.

$$\mathrm{WI}(\%) = [\{\mathrm{Ywf} - \mathrm{Yt})^{*}100\}/\mathrm{Ywf}] \tag{1}$$

where Y_{wf} and Y_t are bulb yields in weed-free check and treatment, respectively.

Selected growth and yield variables of onions were recorded following standard procedures and analyzed statistically to draw valid conclusions. Five plants were selected randomly from each plot measuring 80 m^2 at 100 DAT, and their height was recorded in cm. The onion leaf area was recorded using a leaf area meter (LI-COR 3100, LI-COR, Inc., Lincoln, NE) at 100 DAT.

Soil temperature (maximum and minimum) was recorded on a daily basis for a period of 1 week during the bulb development stage using a digital soil thermometer (model 6300).

The gross returns were calculated by converting the harvest into monetary terms at the current market rate throughout the course of the studies for each treatment.

The net returns were calculated by subtracting the cost of cultivation from the gross returns.

Net returns are calculated as (Gross returns − Total cost of cultivation) plus the benefits of each treatment. The cost ratio was calculated by dividing the net returns by the cultivation cost of the respective treatments.

$$\text{Net benefit : cost ratio (Net B : C)} = \frac{\text{Net return (INR)}}{\text{Total cost of production (INR)}}$$

The net benefit-cost ratio is a financial metric used to evaluate the economic feasibility and attractiveness of an investment and is commonly employed in cost-benefit analysis to assess whether

TABLE 1 Experimental treatment details.

Treatments	Treatment description	Treatment short forms
Crop establishment methods		
Flat-bed transplanting	The crop was transplanted on a well-prepared flat bed.	Flat-trans
Raised bed without residue cover	4-week-old seedlings of onion were transplanted on raised beds, leaving the furrows for irrigation. No residues were applied.	FIRBS – res
Raised bed with residue cover	4-week-old seedlings of onion were transplanted on raised beds, leaving the furrows for irrigation. The residues from the previous season's rice crop (3 t/ha) were applied as mulch.	FIRBS + res
Weed management practices		
Pendimethalin 1.0 kg a.i./ha (PE)	Pendimethalin was applied 2 days after transplanting (DAT) as PE	Pendi
Pendimethalin 0.5 kg a.i./ha (PE), followed by (*fb*) ethoxysulfuron 15 g a.i./ha (post-emergence; POE)	Pendimethalin was applied at 2 DAT and ethoxysulfuron at 30 DAT.	Pendi-ethoxy
Pendimethalin 0.5 kg a.i./ha PE *fb* quizalofop-p-ethyl 50 g/ha (POE)	Pendimethalin was applied at 2 DAT and quizalofop-p-ethyl at 30 DAT.	Pendi-quizalo
Pendimethalin 0.5 kg a.i./ha (PE) *fb* imazethapyr 100 g a.i./ha (POE)	Pendimethalin was applied at 2 DAT and imazethapyr at 30 DAT.	Pendi-imaze
Un-weeded check	No weed control options were adopted throughout the cropping season.	UWC
Weed-free check	Weeds were removed manually from the plots throughout the cropping season so as to maintain the plots free from weeds.	WFC

Trade name for the herbicides. Pendimethalin, Stomp; Ethoxysulfuron, Sunrice; Quizalofop-p-ethyl, Targa super; and Imazethapyr, Pursuit.

the benefits derived from an investment are higher than the costs incurred. A net benefit-cost ratio >1 indicates that the benefits outweigh the costs, suggesting that the study or project is economically viable. On the other hand, a ratio <1 may imply that the costs exceed the benefits, potentially signaling a less favorable investment.

2.2 Statistical analysis

The analysis of variance (ANOVA) test was employed to analyze all the data collected from the randomized block design (Gomez and Gomez, 1984). The least significant difference (LSD) test was employed for the analysis of variance. RStudio software, version 2022.12.0, was used for the statistical analysis (RStudio Team, 2020).

2.3 Crop quality

2.3.1 Total soluble solids

Total soluble solids were measured using a digital refractometer (Atago, Model Pal-1).

2.3.2 Dry matter (%)

Onion bulbs dry matter (%) was determined following the method described by Ranganna (2014). Fresh onion bulbs were finely chopped using a stainless-steel knife, and a 50-g portion was selected for analysis. The selected sample was then placed in a hot air oven (Thermotech TIC-4000) equipped with a thermostat regulator. The samples were dried at a temperature of 50 ± 5°C until a constant weight was attained.

2.3.3 Total phenolics

Total phenolic content was estimated spectrophotometrically using the Folin-Ciocalteu reagent, following the method described by Singleton et al. (1999). Gallic acid was used as a standard for comparison. To perform the analysis, 100 µl of appropriately diluted sample extract was combined with 2.9 ml of distilled water and 0.5 ml of the Folin-Ciocalteu reagent. After 3 min, 2 ml of a 20% Na_2CO_3 solution was added to the mixture. The resulting solution was allowed to stand for 1 min in a boiling water bath and then cooled to ambient temperature. The absorbance of the solution was measured at 760 nm using a UV-Vis spectrophotometer (Systronics, model 117). The total phenolic content was quantified and expressed as µg gallic acid equivalents (GAE) per ml.

2.3.4 Total flavonoid content

The determination of flavonoid content was performed following the method described by Zhishen et al. (1999). A known volume (1 ml) of the methanol-extracted sample was taken as an aliquot in a 13 × 100 mm test tube at the initial time. To the aliquot, 0.3 ml of a 5% sodium nitrite solution was added and allowed to stand for 5 min at room temperature. The reaction was then advanced by adding 0.3 ml of a 10% aluminum chloride solution and allowing it to stand for an additional 6 min. Subsequently, 2 ml of 1 M sodium hydroxide (NaOH) solution was added. The final volume was adjusted to 5.0 ml by adding 2.1 ml of distilled water, and the mixture was thoroughly but gently mixed. The absorbance of the resulting solution was measured at 510 nm against a blank (water). The flavonoid content was expressed as μg quercetin equivalents per ml.

2.3.5 Cupric reducing antioxidant capacity

The cupric reducing antioxidant capacity (CUPRAC) was estimated following the method described by Apak et al. (2004). A 100 μl suitably diluted sample was added to the reaction mixture containing 1 ml of copper chloride solution 10^{-2} M, 1 ml of ammonium acetate (pH 7.0) and 1 ml of freshly prepared neucoproine solution 7.5×10^{-3} M in ethanol, and the volume was made to reach a total of 4.1 ml by adding double distilled water. The tubes were sealed, and after 1 h, the absorbance at 450 nm was recorded against a reagent blank. Results were expressed as μmol Trolox/ml.

2.3.6 Ferric reducing antioxidant power

The ferric reducing antioxidant power (FRAP) assay for antioxidant activity was estimated following the procedure described by Benzie and Strain (1996). A volume of 100-μl sample was mixed thoroughly with 3 ml FRAP reagent consisting of 10 mM 2,4,6-tripyridyl-S-triazine (TPTZ) in 40 mM HCl and 20 mM ferric chloride in 300 mM sodium acetate buffer (pH 3.6) in the ratio of 1:1:10 (v/v). After standing at ambient temperature (20°C) for 4 min, absorbance at 593 nm was noted against a water blank. Results were expressed as μmol Trolox/ml.

3 Results

3.1 Effect on onion growth and yield attributes

The cultivation of the onion crop on raised beds demonstrated advantages over flat sowing, and the incorporation of crop residues further enhanced various growth parameters, as indicated in Table 2. Although there were no significant differences in plant height among different crop establishment systems and weed management practices, the un-weeded check treatment exhibited the maximum plant height (42.9 cm), while pendi-imaze resulted in the lowest (34.2 cm) plant height. Notably, onion leaf area was significantly higher on raised beds with residue (439.5 cm²/5 plants) compared to flat-bed transplanting (381.4 cm²/5 plants). Weed-free check recorded the highest leaf area (456.7 cm²/5 plants), statistically similar to the sequential application of pendi-quizalo treatment (426.9 cm²/5 plants). In contrast, pendi treatment significantly increased leaf area (373.7 cm²/5 plants), while the un-weeded check exhibited the lowest value (219.5 cm²/5 plants).

Regarding bulb characteristics, the raised bed with residue treatment yielded the highest dry bulb weight (220.6 g/5 plants), followed by the raised bed without residue (196.7 g/5 plants) and the flat-bed transplanting treatment (176.0 g/5 plants). Among weed management treatments, the weed-free check resulted in the maximum dry bulb weight (256.2 g/5 plants), with pendi-quizalo statistically comparable. While dry stem weight and yield did not significantly differ across crop establishment systems, weed-free and pendi-quizalo treatments showed significantly higher dry stem weights. Pendi-ethoxy treatment resulted in the lowest dry bulb weight (112.5 g/5 plants). The weed-free check exhibited ~61% higher dry bulb weight compared to the un-weeded treatment. Onion bulb yield was highest in the weed-free check treatment (40.33 t/ha), representing a 99.8% increase compared to the un-weeded check treatment (20.37 t/ha). Pendi-quizalo treatment demonstrated the highest benefit-cost ratio (4.52), followed by the weed-free check (4.13). The interaction analysis between crop establishment systems and weed-free check practice revealed that the combination of raised beds with residue and pendi-quizalo was the second most effective treatment for onion bulb yield (Figure 2). The combination of pendimethalin and quizalofop-p-ethyl may have resulted in a synergistic effect, enhancing the overall efficacy of weed control. Synergies between herbicides can lead to a more comprehensive and lasting suppression of weed growth.

3.2 Weed parameters

Raised beds with residue (FIRBS + res) treatment reduced the weed population, fresh weight, and dry weight of weeds significantly over other crop establishment practices (Table 3). More weed plants per unit area were reported in flat transplanting (80 plants/m^2) compared with FIRBS-residue (62 plants/m^2) and FIRBS + residue (54 plants/m^2) treatments, respectively. Among different herbicidal treatments, the highest weed density was recorded by pendi-imaze (100 plants/m^2), followed by pendi-ethoxy, pendi alone, and pendi-quizalo with 84, 76, and 44 plants/m^2, respectively. Similarly, the fresh and dry weights of weeds followed an identical pattern (Table 3). Application of pendi-quizalo recorded significantly less fresh (153.6 g/m^2) and dry weight (39.6 g/m^2) of weeds/m^2. The weed index, which represents the percent yield loss, was higher in flat bed transplanting (45.7%) than in raised bed systems. Among the weed management practices, it was observed that the highest yield reduction of 83.4% was observed in pendi-imaze, followed by 78.61% in pendi-ethoxy treatment, and the lowest yield reduction of 10.31% was obtained in pendi-quizalo treatment. It is worthwhile to mention here that even the yield reduction recorded in un-weeded check was less compared to pendi-imaze and pendi-ethoxy treatments.

3.3 Soil temperature

In this study, it was observed that crop residue (as mulch) had a great influence on maintaining soil temperature (Table 4). For every crop, there are certain well-defined cardinal temperatures for getting their best performance and higher productivity. Using crop residues as mulch has several benefits, such as maintenance of soil temperature, conservation of moisture, and reduction in weed infestation. FIRBS + res recorded a lower maximum soil temperature and a higher minimum soil temperature compared to other establishment systems. A relatively higher maximum soil temperature range was obtained in the conventional flat-trans system, whereas it became narrower in the bed-planting system.

TABLE 2 Effect of crop establishment methods and weed management practices on crop growth and bulb yield of onion (pooled data for 2016–17 and 2017–18).

Treatments	Plant height (cm)	Leaf area (cm^2/5 plants)	Dry bulb weight (g/5 plants)	Dry stem weight (g/5 plants)	Yield (t/ha)	B:C ratio
Crop establishment systems						
Flat trans	35.23	381.43	176.03	14.58	22.04	2.63
FIRBS – res	39.03	431.8	196.67	13.89	23.06	2.62
FIRBS + res	38.05	439.5	220.56	13.0	24.61	2.74
LSD ($p = 0.05$)	NS	10.59	18.41	NS	NS	–
Weed management options						
Pendi	40.8	373.7	220.3	14.0	24.5	2.81
Pendi-ethoxy	35.7	331.4	113.5	12.7	10.52	0.61
Pendi-quizalo	39.0	426.9	248.5	16.0	36.58	4.52
Pendi-imaze	34.2	313.3	124.0	12.3	9.11	0.37
UWC	42.9	219.5	120.2	10.4	20.37	2.21
WFC	38.7	456.7	256.2	16.7	40.33	4.13
LSD ($p = 0.05$)	NS	41.23	10.48	2.3	1.37	–

LSD, least significant difference at the 5% level of significance ($P = 0.05$).

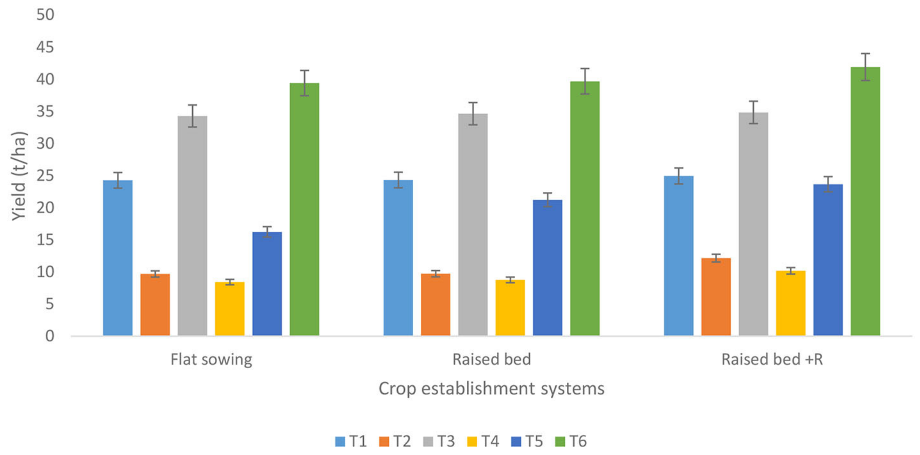

FIGURE 2
Interaction effect of herbicides and crop establishment systems on onion bulb yield (t/ha). T_1, Pendimethalin 1.0 kg a.i./ha (PE); T_2, Pendimethalin 0.5 kg a.i./ha (PE) fb ethoxysulfuron 15g a.i./ha (PE; POE); T_3, Pendimethalin 0.5 kg a.i./ha PE fb quizalofop-p-ethyl 50 g/ha (POE); T_4, Pendimethalin 0.5 kg a.i./ha (PE) fb imazethapyr 100 g a.i./ha (POE); T_5, Un-weeded check; T_6, Weed -free check.

Similar trends have been observed during the second year of the study.

3.4 Crop quality

Among the crop establishment systems, dry matter accumulation (%), total soluble solids (TSS), total phenols, and FRAP activity were found to be the highest in the FIRBS – res treatment compared to other establishment systems. However, flavonoid content and CUPRAC activity were higher in the flat transplanting system (Table 5). Total soluble solids, total phenol content, CUPRAC, and FRAP activity varied significantly among the different weed management practices, and the pendi-quizalo treatment recorded the maximum total phenol and total soluble solids content, significantly higher than other treatments. Maximum flavonoid content was registered with the weed-free check but remained on par with pendi-quizalo. However, CUPRAC and FRAP activity were found to be significantly higher in pendi-quizalo alone and weed-free check, respectively. Although the dry matter accumulation of onions did not vary significantly, the maximum dry matter accumulation was obtained in a weed-free check followed by pendi-quizalo alone treatment.

TABLE 3 Effect of crop establishment systems and weed management practices on weed parameters (pooled data 2016–17 and 2017–18).

Treatments	Weed population (plant/m^2)	Fresh weight of weeds (g/m^2)	Dry weight of weeds (g/m^2)	Weed index (%)
Crop establishment systems				
Flat-trans	80.0	298.4	70.4	45.7
FIRBS – res	62.0	256.8	66.1	34.6
FIRBS + res	54.0	226.4	60.2	32.2
LSD ($p = 0.05$)	7.0	29.5	3.91	–
Weed management options				
Pendi	76.0	270.8	68.6	21.6
Pendi-ethoxy	84.0	321.6	85.6	78.6
Pendi-quizalo	44.0	153.6	39.6	10.3
Pendi-imaze	100.0	349.2	79.6	83.4
UWC	152.0	556.4	138.2	52.6
WFC	00	00	00	00
LSD ($p = 0.05$)	31.18	110.50	22.34	–

LSD, least significant difference at the 5% level of significance.

TABLE 4 Effect of crop establishment method and residue retention on soil temperature.

Max. soil temperature (°C)				Min. soil temperature (°C)			
Date	FIRBS – res	FIRBS + res	Flat-trans	Date	FIRBS – res	FIRBS + res	Flat-trans
27 April 18	29.1	28.3	29.8	27 April 18	18.0	18.8	18.0
28 April 18	29.0	28.2	29.7	28 April 18	18.2	19.2	18.4
29 April 18	29.3	28.5	30.9	29 April 18	18.7	19.5	18.5
30 April 18	29.2	28.8	30.6	30 April 18	19.4	20.1	19.3
01 May 18	29.1	27.7	30.1	01 May 18	16.7	18.4	16.1
02 May 18	28.8	27.9	30.4	02 May 18	16.5	18.1	16.6
03 May 18	29.5	28.1	30.9	03 May 18	19.5	20.3	19.0

4 Discussion

4.1 Growth and yield attributes of onions

The onion crop grown on beds had an edge over the flat sowing, and the incorporation of crop residues showed an additional positive impact on the growth parameters of onion and onion dry bulb yield (Table 2). Improved bulb formation and enhanced yield could be attributed to the presence of friable soil in the beds, which creates a favorable environment (Kaur et al., 2020a). This type of soil promotes better root proliferation and ensures sufficient moisture availability, leading to robust crop growth and plant vitality (Bana et al., 2015). Additionally, incorporating crop residues offers extra advantages such as conserving soil moisture by preventing water evaporation from the surface (Bana et al., 2020; Faiz et al., 2022). Furthermore, it aids in effective weed control by depriving weeds of light and space to grow and compete with the onion crop (Kaur et al., 2020b). Under similar ecologies, raised beds with residue recorded higher pea yields than raised beds without residue because of the positive impacts of crop residues in reducing crop-weed competition (Kaur et al., 2020a), as residue retention on the soil surface produced a soil microclimate that was much more conducive to crop growth (Singh et al., 2018). Hence, the lesser crop-weed competition provided a congenial microclimate for better onion growth, resulting in a higher bulb yield in the raised bed along with residue incorporation.

The pendi-quizalo treatment exhibited a significantly higher leaf area, attributed to reduced crop-weed competition. In contrast, the un-weeded control treatment recorded the lowest leaf area, likely due to a higher weed population dominating resources such as sunlight, nutrients, and moisture over the crop plants. This phenomenon resulted in suppressed growth of onion and a subsequent reduction in leaf area. Similar findings have been reported in studies by Sable et al. (2013), Kaur et al. (2018), Kaur et al. (2020a,b), and Sen et al. (2020). Approximately 106% more dry bulb weight and 80% more yield were noticed in pendi-quizalo treatment over un-weeded control treatment. Greater yields under sequential application of herbicides might be due to early emerged weeds having been controlled by pre-emergence application of pendimethalin, and the later growing weeds might be controlled

TABLE 5 Effect of crop establishment methods and weed management practices on the quality of onions (pooled data 2016–17 and 2017–18).

Treatments	Dry matter of crop (%)	TSS (Brix)	Total Phenol (μg GAE/ml)	Flavonoid (μg Quercetin/ml)	CUPRAC	FRAP (μmol Trolox/ml)
Crop establishment systems						
Flat-trans	13.04	12.81	975.56	358.85	2.01	1.011
FIRBS – res	13.40	13.51	1365.89	336.17	1.81	1.168
FIRBS + res	14.28	13.3	898.78	352.48	1.56	1.073
LSD ($p = 0.05$)	NS	1.089				0.336
Weed management options						
Pendi	14.43	13.5	1040.7	379.63	1.87	0.987
Pendi-ethoxy	12.96	12.68	1044.9	319.78	1.77	0.951
Pendi-quizalo	14.16	13.91	1331.8	420.63	1.83	1.220
Pendi-imaze	13.79	12.88	1172.9	308.78	1.76	1.200
UWC	11.05	13.37	951.33	305.85	1.69	1.002
WFC	14.50	12.9	1296.9	440.33	1.83	1.222
LSD ($p = 0.05$)	5.82	0.3144	449.423	39.31	0.07963	0.2981

by the post-emergence application of quizalofop-p-ethyl. As the experimental field was dominated by grassy weeds, quizalofop-p-ethyl being a grass killer might have been more effective in controlling weeds over other herbicides used (Kaur et al., 2020a; Sen et al., 2020). Dry weight of stem, although did not differ significantly over crop establishment systems, but significantly higher dry stem weight was found in weed-free check and it remained at par with pendi-quizalo treatment which might be because of comparatively lesser competition by the weeds in these two treatments. Onion bulb yields differ significantly over weed-free check followed by pendi-quizalo treatment and pendi-quizalo alone treatment because of better weed control in these treatments. The treatment with pendi-quizalo achieved the highest benefit-to-cost ratio of 4.52, closely followed by the weed-free check treatment with a ratio of 4.13. Despite the weed-free treatment resulting in higher yields, the overall benefit-to-cost ratio was lower due to the higher labor wages associated with this particular treatment.

4.2 Weed parameters

Raised bed with residue treatment reduced the weed population, fresh weight, and dry weight of weeds significantly over other crop establishment systems, which might be due to the lesser light and space available for the weeds to grow in the residue mulched condition (Bana et al., 2016; Bamboriya et al., 2017; Kaur et al., 2020a). The weed index, which represents the percent yield loss, was higher in flat bed transplanting (45.7%) than in raised bed transplanting. This might be because of higher weed dry matter, density, and crop-weed competition in the crop grown in the FB transplanting system (Mishra et al., 2022). Among the weed management practices, it was observed that weed-free checking caused the greatest reduction in weed density and weed dry matter production. Application of pendi-quizalo recorded a significantly lesser number and fresh and dry weight of weeds/m^2 and a lower weed index (Table 3) because of the integration of pre- and post-emergence herbicides along with crop residues, which created a weed-free environment for the entire crop growing period. The results are in agreement with Dudi et al. (2011), Tripathy et al. (2013), Kaur et al. (2018), and Sen et al. (2021).

4.3 Soil temperature

The application of crop residue as mulch exerted a significant influence on the maintenance of soil temperature, as illustrated in Table 4. The utilization of crop residues as mulch presents numerous advantages, such as the effective regulation of soil temperature, conservation of moisture, and reduction in weed infestation (Bamboriya et al., 2017). Winter onion thrives under lower temperature conditions, conducive to various physiological developmental stages, including bulb development. Notably, a sudden increase in temperature during the bulb development stage can significantly abbreviate the bulb yield.

Bed planting combined with residue application maintains the maximum soil temperature at lower levels, thereby facilitating the grain-filling process (Kaur et al., 2020b). The system of bed planting with residue (FIRBS + res) recorded a lower maximum soil temperature and a higher minimum soil temperature when compared to other establishment systems, such as FIRBS without residue (FIRBS – res) and flat transplanting. It is noteworthy that FIRBS + res demonstrated a higher minimum soil temperature, followed by FIRBS – res and flat transplanting, as detailed in Table 4. This underscores the efficacy of mulch application in creating an optimal soil temperature regime conducive to enhanced winter onion (*Allium cepa* L.) productivity and quality while effectively managing mixed weed flora.

4.4 Crop quality

Long storage life has been proven to be correlated with high total soluble solids (TSS) (AVRDC, 2000, 2008). Depending on the specific cultivar (Mogren et al., 2006; Yoo et al., 2010) and environmental growing scenarios, onion flavonoid concentration has been shown to vary (Wakchaure et al., 2023). Natural elicitors have been reported to have an impact on flavonoids (Al-Tawaha et al., 2006; Sagar et al., 2020). In addition, the production of flavonoids occurs in response to pathogen infection, chemical or UV-induced physical harm, or both (Panche et al., 2016). The phytotoxic effect of herbicides on crops may also increase the flavonoid content. Among the several crop establishment practices followed in this study, total soluble solids (TSS), total phenol, and FRAP activity were found to be highest in flat beds without residue conditions compared to other establishment systems. Flavonoid content and CUPRAC activity were higher in the flat bed transplanting method, but dry matter percent was highest in bed planting with residue, which might be because of favorable growing conditions on the beds as well as more friable soil volume for good growth and bulb development, in addition to more moisture availability and lesser crop weed competition in the FIRBS with residues (Mishra et al., 2022).

Total soluble solids, total phenol content, CUPRAC, and FRAP activities varied significantly among the different weed management practices; the pendi-quizalo treatment recorded the maximum total phenol and total soluble solid content, which was significantly higher than other treatments. Angmo and Chopra (2020) found that pendimethalin 1 kg/ha as pre-emergence fb quizalofop-ethyl 0.05 kg/ha at 40 DAT caused a slight phytotoxic effect. This might be the reason for the higher flavonoid content in the pendi-quizalo treatment. Long storage life has been proven to be correlated with high total soluble solids (TSS) (AVRDC, 2000, 2008). When compared to cultivars with the lowest yields, cultivars with high bulb yields may have a lower total soluble solids content (Yemane et al., 2013). Significantly negative correlations between bulb weight and soluble solids concentration were also found by Mallor et al. (2011). Flavonoid content was registered at its maximum with the weed-free check but remained at par with the pendi-quizalo treatment. Weed pressure has been reported to increase flavonoids in soybeans, despite the fact that any findings in the literature regarding the impact of weeds on flavonoid levels in onions are lacking (Al-Tawaha and Seguin, 2006). Contrarily, the opposite result has been found in this study, which indicated higher flavonoid content in weed-free check plots. However, CUPRAC and FRAP activities were found to be significantly higher in pendi alone treatment and weed-free check, respectively.

5 Conclusion

Based on the field and laboratory studies, it could be concluded that prolonged weed infestation in onion crops leads to a substantial decline in yield, but a comprehensive approach combining pre- and post-emergence herbicides, along with the integration of weed management practices, could effectively mitigate weed growth. Moreover, integrating weed management practices such as incorporating crop residues and transplanting onions on beds further enhanced crop yield and various growth parameters, while also reducing weed density and the accumulation of weed dry matter. Among the different treatments evaluated, the most favorable results were obtained with the application of pendi-quizalo in combination with FIRBS (furrow-irrigated raised bed system) and crop residue incorporation. This treatment demonstrated the highest levels of total phenols and total soluble solids compared to other treatments, and the differences were statistically significant.

5.1 Future line of work

Further investigations could involve examining the interaction between herbicide application timing and agronomic practices such as residue incorporation, transplanting techniques, irrigation methods, and nutrient management. By evaluating multiple combinations of herbicides and agronomic practices, researchers can identify the most effective and sustainable strategies for managing weeds and maximizing onion crop yield and quality.

In addition to yield parameters, future studies could also delve deeper into quality parameters, including nutritional content, flavor compounds, and other sensory attributes of onion bulbs. Understanding the influence of herbicides and agronomic practices on these quality aspects is essential for meeting consumer preferences and market demands.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RK: Conceptualization, Supervision, Writing – original draft. RB: Data curation, Visualization, Writing – review & editing. TS: Formal analysis, Supervision, Writing – review & editing. SM: Formal analysis, Writing – review & editing. RR: Formal analysis, Validation, Writing – review & editing. AD: Data curation, Writing – review & editing. PG: Visualization, Writing – review & editing. JG: Data curation, Validation, Writing – review & editing. SuK: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft. SS: Data curation, Visualization, Writing – review & editing. ShK: Formal analysis, Visualization, Writing – review & editing. AC: Data curation, Visualization, Writing – review & editing. TD: Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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