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RESEARCH ARTICLE

Evaluation of herbicide mixtures for broad-spectrum weed suppression and yield improvement in onion (*Allium cepa* L.) under post rainy season conditions

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Abstract

Onion (*Allium cepa* L.) is highly susceptible to weed infestation because of its slow initial growth, short stature, shallow roots and lack of dense foliage. The weed problem severely influences crop growth and bulb yield. In most production systems, weed control relies on manual weeding, which is labour-intensive and costly. Therefore, the current investigation was carried out at the Agronomy Main Research Farm of Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India to evaluate different herbicides application and their effect on weed and crop growth. The experiment was laid out under post rainy season during December to March consecutively for 2 years in randomized block design with 8 treatments and 3 replications. Application of Oxyfluorfen 23.5 % emulsifiable concentrate (EC) at 100 g a.i. ha^{-1} followed by a post-emergence ready mix (RM) application of quizalofop-ethyl 4 % + oxyfluorfen 6 % EC at 100 g a.i. ha^{-1} resulted in higher weed control efficiency (WCE) (83.83 %) and herbicidal efficiency index (HEI) (18.84 %). The yield advantage was approximately 275 % over weedy check and 31 % over 3 manual weeding ($p \leq 0.05$). The desirable yield traits like bulb equatorial diameter, polar diameter, neck thickness, percentage of bolters, doubles and different grades of (A, B and C) bulbs were significantly influenced with the above combination of herbicide over all tested herbicides and manual weeding. The residue analysis of harvested soil and crop through high-performance liquid chromatography (HPLC) analysis showed residues below the maximum residue limit (MRL). The result confirms that Oxyfluorfen 235 % EC at 100 g a.i. ha^{-1} fb Quizalofop-ethyl 4 % + Oxyfluorfen 6 % EC (RM) at 100 g a.i. ha^{-1} is a suitable herbicide combination for managing broad spectrum weeds in onion.

Keywords: bulb yield; herbicide; onion; weed growth

Introduction

Onion (*Allium cepa* L.) is an oldest bulbous crop known for its pungent flavour, making it a vital ingredient in various regional cuisines and earning the title "Queen of the kitchen" (1). The major onion producing countries are India, China, Pakistan, Netherlands, Bangladesh and Australia. In India, onion is cultivated over 1.74 million hectares, with a production of 30.21 million tonnes and an average productivity of 17.35 t ha^{-1} in 2023–24 whereas in Odisha covers an area of 32000 ha, producing 4.75 lakh tonnes with productivity of 14.8 t ha^{-1} (2).

One of the major constraints in onion cultivation is heavy weed infestation. The competitive ability of onion with weeds is very poor due to its shallow root system, non-branching habit, short stature, cylindrical upright tapered leaves and extremely slow early-stage growth (3). Frequent application of irrigation and fertilizer also aggravates the situation by promoting successive weed flushes. As a result, onion fields are often infested with various broadleaf and grassy weeds, leading to significant yield losses.

Uncontrolled weed presence can drastically reduce bulb yield by 40–80 % depending on the severity and duration of weed competition in the field (4, 5). Yield losses are accompanied by reduced bulb size and increased incidence of undesirable traits such as double bulbs and bolters (6, 7). This scenario underscores the necessity for effective weed management practices during critical growth stages to achieve optimal economic yields.

Conventional weed control methods, such as hoeing and hand weeding (HW), are labour intensive, costly and often ineffective, particularly in onion cultivation due to the close plant spacing and shallow root systems. Although manual weeding is widely practiced, it is time consuming, can cause plant damage and is hindered by labour shortages during peak periods (3, 8). Consequently, herbicides offer a more efficient and suitable alternative for weed control, making it essential to implement appropriate herbicide-based weed management strategies. This

approach is not only cost-effective but also remunerative for onion growers (8, 9).

Chemical weed management in onion involves pre-emergence (PRE) or post-emergence (POST) application of selective herbicides such as pendimethalin, oxyfluorfen, oxadiazon, quizalofop -ethyl, alachlor, butachlor and metolachlor, often followed by HW, which are used alone or in different combinations (3, 5, 10–14).

Previous studies indicate that a single herbicide application is insufficient to manage complex and sequential weed emergence patterns. Later weed flushes coincide with intercultural operations further complicate weed control. Therefore, either the integration of chemical herbicides with manual or mechanical control or selection of herbicides sequentially will rather help in controlling the weed flora to a considerable extent in the onion crop (8, 15–18).

Considering shifts in weed flora driven by cropping pattern changes and climate variability, the sole application of pre-emergence will not only be sufficient to control the diverse weed flora in later stages of crop growth but also invite resistance problem due to its repeated use.

Pre-mix or ready-mix herbicides provide broad-spectrum control and may reduce the risk of resistance development (19). These formulations are gaining popularity because they allow convenient single-application use. Hence, these herbicides, both as sole and sequential applications, require evaluation to determine their comparative efficacy.

Ready-mix combinations of oxyfluorfen (PPO inhibitor) with quizalofop-ethyl or propaquizafop (ACCase inhibitors) target pigment and fatty acid biosynthesis in susceptible weeds (20). The selectivity of herbicides largely depends on dose, time, crop and stage (21). Limited research is available on the selectivity and efficacy of Oxyfluorfen + Quizalofop-ethyl or Propaquizafop ready-mixes in onion.

Considering the above facts, the experiment was carried out with an objective to evaluate the performance of sole, sequential and ready-mix herbicide applications on weed suppression and crop response. The working hypothesis was that sequential and ready-mix herbicide applications would provide superior weed control and yield benefits compared to single-application or sole herbicides.

Materials and Methods

Site description

The present field experiment was conducted at the All India Coordinated Research Project (AICRP) on Weed Management Block, Agronomy Main Research Farm of the Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (20°15' N latitude and 85°52' E longitude, with an elevation of 25.9 m above the mean sea level and a distance of 64 km away from the Bay of Bengal), India. The study site falls under the East and South Eastern Coastal Plain Agro-climatic zone of Odisha. In the 2022–23 and 2023 –24 cropping seasons, the experimental site received 96 mm and 100.3 mm rainfall with 4 and 9 rainy days respectively, the mean maximum and minimum temperatures were 31.35 °C and 18.08 °C during 2022–23, 30.4 °C and 18.9 °C during 2023-24, while the mean bright sunshine hours were 4.81 hr day^{-1} and 3.8 hr day^{-1} and the mean wind velocity was 1.4 km hr^{-1} and 2.9 km hr^{-1}, respectively. The soil at the experimental field is classified as Alfisols (sub-order Ustalfs, great group Haplustalf, sub-group Ultic Haplustalfs), belonging to the fine loamy, mixed, hyperthermic family with a sandy-loam texture. Chemical analysis of the upper 15 cm of soil indicated a high organic carbon content of 0.79 %, medium available nitrogen (376.32 kg ha^{-1}) determined by the alkaline potassium permanganate method, low available phosphorus (12.32 kg ha^{-1}) as measured by Bray's No.1 method, medium available potassium (150.53 kg ha^{-1}) measured using a Flame photometer and an acidic soil pH of 5.1 (1:2.5 soil: water ratio) (22–25).

Description of experiment

The field experiment was carried out with 8 treatment combinations (Table 1) in a randomized block design with 3 replications during post rainy season (December to March), consecutively for 2 years i.e., 2022–23 and 2023–24. The 45 days old onion seedlings of variety, Nasik Red (N-53) were treated for 10 min with a Bavistin solution (0.5 g L^{-1}) to protect the crop from fungal diseases. The seedlings were then manually transplanted on 4th December 2022 and 6th December 2023 into plots of size 7m × 4m with a row geometry of 20 × 15 cm. The crop was fertilized with nitrogen (50 kg ha^{-1}), P_2O_5 (75 kg ha^{-1}) and K_2O (100 kg ha^{-1}) through urea, single super phosphate and muriate of potash, respectively, as a basal application at the time of transplanting. The remaining 50 kg ha^{-1} of nitrogen in the form of urea was applied as a top dressing in 2

Table 1. Treatment details adopted in the experiment

Treatments	Herbicide name	Dose	Time of application	Formulation	Trade name (Company)
T_1	Oxyfluorfen	100 g a.i. ha^{-1}	PRE 2 DAT	23.5 % EC	Goal (Dow AgroScinces)
T_2	Quizalofop-ethyl	50 g a.i. ha^{-1}	POST 25 DAT	5 % EC	Targa Super (Dhanuka)
T_3	Oxyfluorfen fb Quizalofop-ethyl	100 g a.i. ha^{-1} fb 50 g a.i. ha^{-1}	PRE 2 DAT fb POST 25 DAT	-	-
T_4	Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM)	100 g a.i. ha^{-1} fb 100 g a.i. ha^{-1}	PRE 2 DAT fb POST 25 DAT	23.5 % EC and 4 % EC + 6 % EC	Goal and Onekil (Dhanuka)
T_5	Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM)	100 g a.i. ha^{-1} fb 148 g a.i. ha^{-1}	PRE 2 DAT fb POST 25 DAT	23.5 % EC and 5 % EC + 12 % EC	Goal and Dekel (Adama)
T_6	Oxyfluorfen fb Fluroxypyr meptyl	100 g a.i. ha^{-1} fb 360 g a.i. ha^{-1}	PRE 2 DAT fb POST 25 DAT	23.5 % EC and 36 % EC	Goal and Starane (Corteva)
T_7	HW at 20, 40 & 60 DAT	-	-	-	-
T_8	Weedy check	-	-	-	-

Abbreviations: PRE: pre-emergence; POST: post-emergence; DAT: days after transplanting; RM: ready-mix; fb: followed by.

equal splits, at 20 and 30 days after transplanting (DAT). At the time of transplanting, the upper one-third portion of the leaves was topped to reduce the rate of transpiration. Immediately after transplanting, a light irrigation was applied for better establishment of the seedlings in the field and subsequent irrigations were given according to the schedule.

The pre-emergence herbicide was applied at 2 DAT and the post-emergence herbicides were applied at 25 DAT. The required quantities of herbicides for 21 m^2 of each experimental plot were applied with 500 L water ha^{-1}. Herbicides were sprayed using a Neptune Battery Operated Knapsack Sprayer BS-12 (200 kPa pressure) of 16 L capacity with a flat fan nozzle to ensure uniform coverage throughout the area. Spraying was conducted during morning hours under calm wind conditions. Weeds were removed by using hand hoe for manual HW at 20 DAT, 30 DAT and 45 DAT. In the unweeded control treatment, no weeding operation was undertaken and weeds were allowed to emerge to assess the dominant weed flora and yield loss. All other recommended management practices were followed for each treatment as and when needed. Onion bulbs were harvested on 20th March 2023 and 22nd March 2024, respectively, when the pseudostem became flaccid and could no longer support the leaf blades (26).

Data collection and calculations

Weed density

The weed density consisting of grasses, sedges and broadleaf weeds assessed by placing a 0.5 × 0.5 m quadrat at three randomly selected locations within each plot and expressed as number per m^2 (no. m^{-2}). The weeds were then removed from the selected quadrat, with roots separated from shoots and oven-dried at 70 ± 1 °C for 72 hr (5). The dry weight of the weeds was measured and expressed in g m^{-2}.

Weed control efficiency (WCE)

To adjudge the efficiency of weed control treatments, weed control efficiency (WCE) was calculated as:

$$WCE\ (\%) = \frac{WDMc - WDMt}{WDMc} \times 100 \quad \text{(Eqn. 1)}$$

Here, WDMc: weed dry weight (g m^{-2}) in unweeded control, WDMt: weed dry weight (g m^{-2}) in treated plot (20).

Weed index (WI)

The weed index (WI) was computed using the following formula:

$$WI\ (\%) = \frac{X - Y}{X} \times 100 \quad \text{(Eqn. 2)}$$

Here, X: yield of bulb (t ha^{-1}) in treatment which has highest yield and Y: yield of bulb (t ha^{-1}) in treatment for which WI is to be calculated, it is expressed in percentage (27).

Herbicidal efficiency index (HEI)

The potential of a particular herbicide for controlling weeds was calculated using the formula:

$$HEI\ (\%) = \frac{\frac{Yt - Yc}{Yc} \times 100}{\frac{WDMt}{WDMc} \times 100} \quad \text{(Eqn. 3)}$$

Here, Yt: yield from treated plot, Yc: yield from control plot, WDMt: weed dry matter in treated plot and WDMc: weed dry matter in control plot (28).

Growth parameters, yield attributes and yield

The neck thickness, equatorial diameter and polar diameter of 10 bulbs from each plot were measured using a vernier calliper after harvesting the crop. Their averages were then calculated and recorded in millimetre (mm). Then the percentage of double bulbs, bolters, A grade, B grade and C grade bulbs were recorded on their weight basis over total bulb yield. However, the grades were determined by equatorial diameter. The bulbs with a diameter of less than 3.5 cm were classified as "unmarketable grade", 3.5 to 4.5 cm as "C grade", 4.5 to 5.5 cm as "B grade", 5.5 to 6.5 cm as "A grade" and those above 6.5 cm as "A+ grade" (16). The total bulb weight per unit plot was measured in kilogram per plot and finally converted into t onnes per hectare.

Herbicide residue in soil and onion bulbs (HPLC method)

Residues of herbicides in soil and onion bulb samples were quantified using high-performance liquid chromatography (HPLC).

Extraction: A representative 20 g sample of air-dried soil or homogenized onion bulb was placed in a conical flask. To this, 50 mL distilled water and 10 mL saturated sodium chloride solution were added. The mixture was shaken on a mechanical shaker for 1 hr to extract Oxyfluorfen and Quizalofop-ethyl residues.

Partitioning: The homogenized extract was filtered through activated charcoal and transferred into a 500 mL separating funnel. The aqueous phase was first partitioned with 50 mL n-hexane:ethyl acetate (2:3, v/v) to remove non-polar interferences and the organic layer was discarded. The remaining aqueous phase was further partitioned twice with 50 mL dichloromethane and the organic layers were combined.

Clean-up and concentration: The combined dichloromethane extract was passed through anhydrous sodium sulphate to remove moisture and concentrated to near dryness using a rotary vacuum evaporator under reduced pressure. The residue was reconstituted in 5 mL HPLC-grade acetonitrile and filtered through a 0.45 µm nylon syringe filter prior to analysis.

HPLC analysis: Residue quantification was performed using HPLC system equipped with a diode array detector (DAD). Separation was achieved on a reverse-phase C18 column (250 × 4.6 mm i.e., 5 µm particle size). The mobile phase consisted of acetonitrile: water (80:20, v/v), delivered at a flow rate of 1.0 mL min^{-1} under isocratic conditions. The injection volume was 20 µL and detection was carried out at 240 nm.

Statistical analysis

The observed data were subjected to statistical analysis following the procedure for a randomized block design using analysis of variance (29). Before the analysis of variance, all data were tested for homogeneity of error variances. Weed count data were square root transformed to address greater variability (30). Treatment means were compared using a protected least significant difference test at $p \leq 0.05$. The ANOVA, correlation analysis and graphing were performed in RStudio.

Results

The weed flora in the experimental field under different herbicide treatments, comprised 21 species, including 9 grasses, 1 sedge and 11 broadleaf weeds. Among the grassy weeds, *Cynodon dactylon*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *Leptochloa chinensis*, *Echinochloa colona*, *Eleusine indica* and *Paspalum scrobiculatum* were observed. *Cyperus rotundus* was the dominant

sedge. The broadleaf weeds, such as *Alternanthera sessilis*, *Amaranthus viridis*, *Cleome viscosa*, *Eclipta alba*, *Euphorbia hirta*, *Parthenium hysterophorus*, *Phyllanthus niruri*, *Physalis minima*, *Portulaca oleracea*, *Spilanthes acmella* and *Tridax procumbens*, were most evident during different stages of crop growth. Among the total weed flora, the relative proportion of grassy weeds (46.95 %) was higher than that of sedges (14.97 %) and broadleaf weeds (38.08 %), expressed as a percentage of the total weed density (Fig. 1).

Data analysis revealed a significant reduction in weed density and dry weight across all weed control treatments compared to the weedy check (Table 2). At 40 DAT in both the years, the lowest weed density was recorded under application of Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) (6.89 m^{-2}). In contrast, the weedy check exhibited the highest weed density (17.08 m^{-2}).

Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) significantly reduced the dry weight of weeds (by 81.1 % at 40 DAT) compared with weedy check.

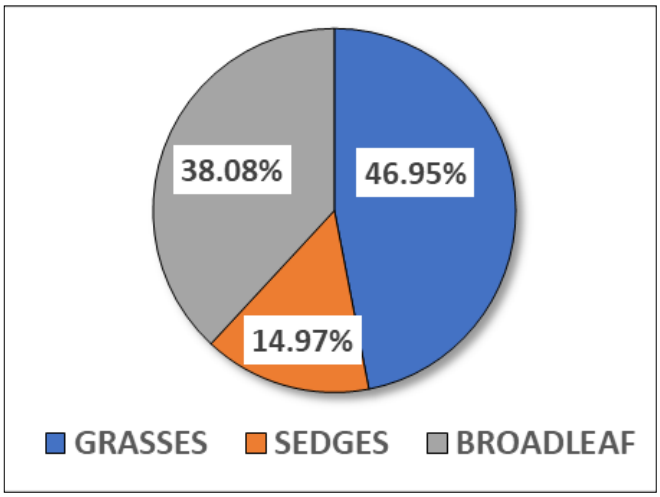

Fig. 1. Occurrences of weed species (%) in onion as influenced by weed management practices.

Weed control efficiency, weed index and herbicidal efficiency index

The WCE, WI and HEI were employed to assess the effectiveness of the various weed control treatments.

Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) (83.83 % at 40 DAT) and Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM) (80.85 % at 40 DAT) resulted in a higher ($p < 0.05$) WCE compared with remaining herbicides. Conversely, Quizalofop-ethyl showed a lower WCE of 43.89 % (Table 2).

The WI (%) for different weed control treatments (Table 2) was determined based on crop yield. The highest WI was observed in the weedy check (73.63 %), followed by Quizalofop-ethyl (36.22 %) and Oxyfluorfen (27.94 %). In contrast, the lowest WI (12.48 %) was recorded in Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM) ($p < 0.05$).

The HEI integrates yield response and weed suppression (Table 2). Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) resulted in higher ($p < 0.05$) HEI (18.84 %) compared with remaining herbicides. HEI followed an order of Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) > Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM) > Oxyfluorfen fb Quizalofop-ethyl > Oxyfluorfen fb Fluroxypyr meptyl > Oxyfluorfen > Quizalofop-ethyl for different herbicides.

Bulb yield attributing parameters and bulb yield

Data analysis showed significant variations in onion bulb diameter and neck thickness due to the application of different weed control treatments (Fig. 2). Significantly, the maximum equatorial and polar diameter was recorded in Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) (50.99 mm and 43.50 mm) which was at par with Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM) (49.61 mm and 42.92 mm) and Oxyfluorfen fb Quizalofop-ethyl (48.49 mm and 41.65 mm). In contrast, a reverse trend was observed for the neck thickness of the bulbs. Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen

Table 2. Weed density (no. m^{-2}), Weed control efficiency (%), Weed index (%) and Herbicidal efficiency index (%) as influenced by different weed control treatments

Treatments	Weed density at 40 DAT (number per m^2)		Weed dry weight at 40 DAT (g m^{-2})		Weed control efficiency at 40 DAT		Weed index (%)		Herbicidal efficiency index (%)	
	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24	2022–23	2023–24
T_1	11.94 (142.67)	11.80 (139.33)	2.80 (7.85)	2.77 (7.66)	49.80	54.31	26.40	29.48	3.83	4.07
T_2	12.78 (163.33)	13.44 (180.67)	3.00 (8.98)	3.15 (9.94)	42.53	43.89	34.29	38.14	2.67	2.55
T_3	8.52 (72.67)	7.88 (62.33)	2.00 (4.00)	1.85 (3.43)	74.49	79.16	16.33	15.57	7.93	8.76
T_4	7.34 (54.00)	6.43 (41.67)	1.72 (2.97)	1.51 (2.29)	81.08	86.57	-	-	18.73	18.95
T_5	8.06 (65.00)	7.01 (49.33)	1.89 (3.58)	1.64 (2.71)	77.12	84.57	13.27	11.70	9.66	11.63
T_6	11.63 (135.33)	10.87 (118.33)	2.73 (7.44)	2.55 (6.51)	52.19	62.32	24.90	25.70	5.09	5.06
T_7	9.38 (88.00)	9.65 (93.33)	2.20 (4.84)	2.26 (5.13)	68.89	71.14	22.86	24.06	5.65	6.48
T_8	16.89 (285.67)	17.27 (298.33)	3.96 (15.71)	4.05 (16.41)	-	-	72.66	74.60	-	-
SE(m) ±	0.214	0.395	0.050	0.060	-	-	-	-	-	-
LSD ($p = 0.05$)	0.650	1.198	0.152	0.182	-	-	-	-	-	-

Original values are given in parentheses, which were transformed to $\sqrt{x}$.

Treatment: - T_1: Oxyfluorfen; T_2: Quizalofop-ethyl; T_3: Oxyfluorfen fb Quizalofop-ethyl; T_4: Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM); T_5: Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM); T_6: Oxyfluorfen fb Fluroxypyr meptyl; T_7: HW at 20, 40 & 60 DAT; T_8: Weedy check.

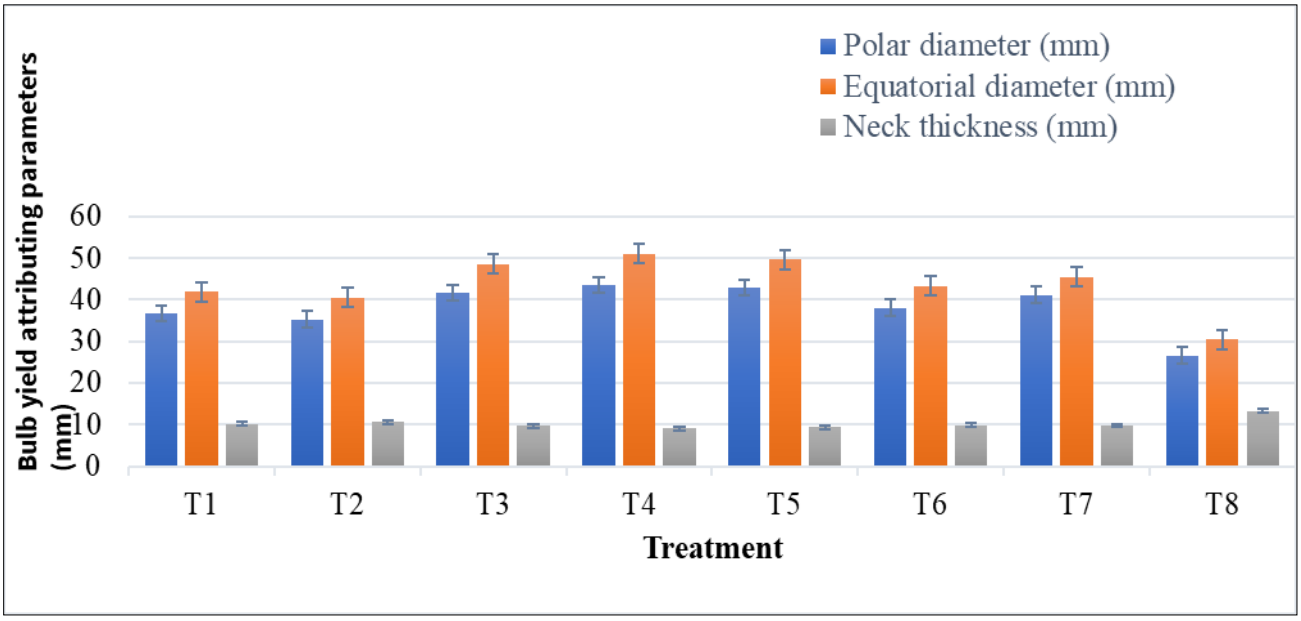

Fig. 2. Bulb diameter (mm) and neck thickness (mm) influenced by different weed control treatment (mean of 2 years). Error bars represent standard error of mean. The details of treatments explained in Table 1.

(RM) recorded the minimum neck thickness (9.14 mm), while the maximum neck thickness was observed in the weedy check (13.29 mm). However, neck thickness did not differ significantly among herbicide-treated plots. This resulted in the production of larger-sized bulbs in the treated plots compared to the weedy check (Fig. 3).

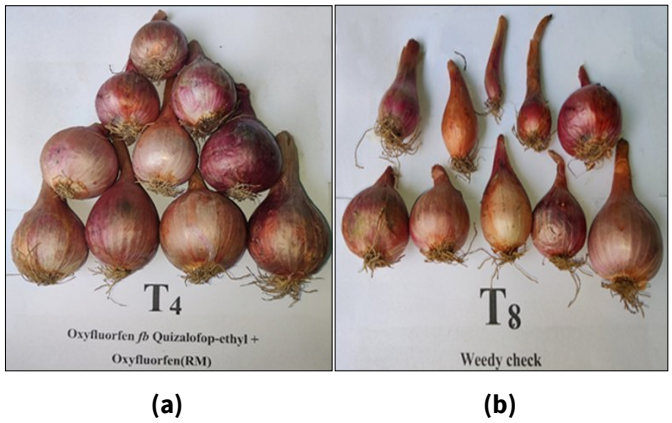

Fig. 3. Bulb size as influenced by weed management treatment Oxyfluorfen 23.5 % EC at 100 g a.i. ha^{-1} fb Quizalofop-ethyl 4 % + Oxyfluorfen 6 % EC (RM) at 100 g a.i. ha^{-1} (a), compared with weedy check (b).

The highest percentage of A grade and B grade bulbs (Fig. 4) was recorded in Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) (29.85 % and 41.54 %), which was at par with Oxyfluorfen fb Propaquizafop + Oxyfluorfen (RM) (28.39 % and 40.56 %) and Oxyfluorfen fb Quizalofop-ethyl (27.84 % and 39.36 %). Weedy check recorded the highest percentage of C grade bulbs (38.15 %). Regarding the percentage of double bulbs and bolters, the minimum 2.79 % of doubles and 2.02 % of bolters were recorded in Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM). In contrast, the maximum 6.78 % of doubles and 4.91 % of bolters were recorded in weedy check. The highest bulb yield (24.50 t ha^{-1} in 2022–23 and 27.56 t ha^{-1} in 2023–24) were produced by the application of Oxyfluorfen fb Quizalofop-ethyl + Oxyfluorfen (RM) (Table 3).

Correlation analysis

The correlation study between weed dry matter with the yield attributing characters and bulb yield revealed that a strong positive association existed with characters like neck thickness (0.93), C grade bulbs (0.99), bolters and double bulbs (0.91). Significant

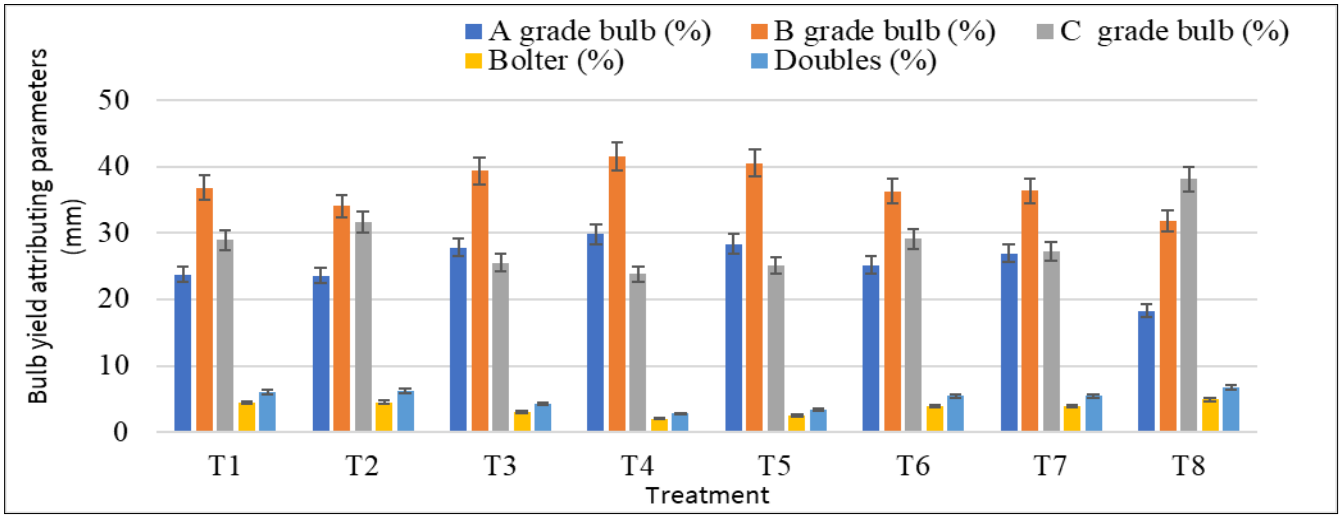

Fig. 4. Percentage of production of bolter, doubles, A, B, C grade bulbs in onion as influenced by different weed control treatments (mean of 2 years). Error bars represent standard error of mean. The details of treatments explained in Table 1.

Table 3. Bulb yield (t ha^{-1}) as influenced by different weed control treatments

Treatments	Bulb yield (t ha^{-1})		
	2022-23	2023-24	Pooled
T_1	18.03	19.43	18.73
T_2	16.10	17.05	16.57
T_3	20.50	23.27	21.88
T_4	24.50	27.56	26.03
T_5	21.25	24.33	22.79
T_6	18.40	20.48	19.44
T_7	18.90	20.93	19.91
T_8	6.70	7.16	6.93
SE(m)±	0.579	1.365	0.741
LSD(p=0.05)	1.756	4.140	1.753

negative correlations were observed between bulb yield (-0.97), polar diameter (-0.99), equatorial diameter (-0.99), A grade (-0.99) and B grade (-0.96) bulbs (Fig. 5).

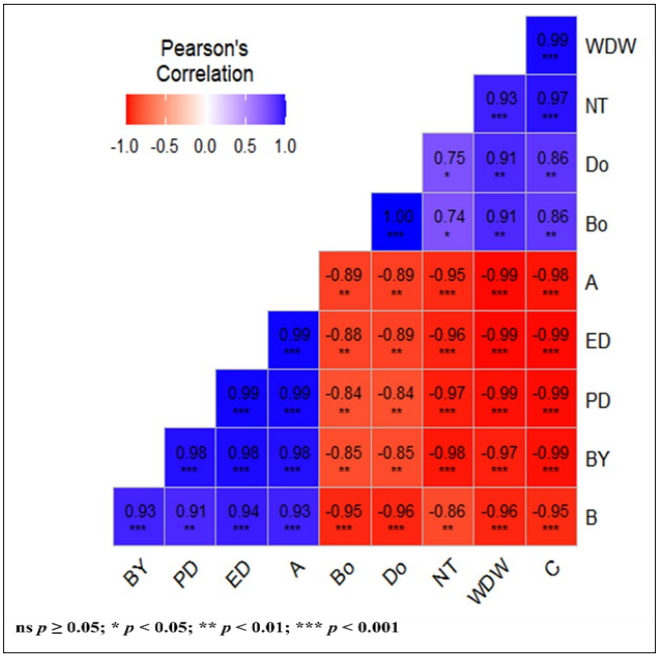

Fig. 5. Pearson correlation coefficient (r) of weed dry weight and bulb yield parameters in onion as influenced by different weed control treatments. A: A grade bulb; B: B grade bulb; C: C grade bulb; Bo: bolters; Do: doubles; PD: polar diameter; ED: equatorial diameter; NT: neck thickness; BY: bulb yield; WDW: weed dry weight.

Herbicide residue in soil and onion bulbs (HPLC Method)

The chromatograph depicted in Fig. 6 showed that the sample collected immediately after application of herbicide, Oxyflurofen + Quizalofop-ethyl (RM) 100 g ha^{-1}. The residue retention was observed to be 0.1728 mg kg^{-1} of soil (Table 4). The sample collected from the onion plant and bulb at harvest was found below the detectable limit (0.01 mg kg^{-1} of sample). Similarly, the harvested soil sample also showed the residue retention of below maximum residue limit (MRL) (0.05 mg kg^{-1} of soil).

Table 4. Residue analysis of Oxyfluorfen + Quizalofop-ethyl (RM) (mg kg^{-1}) in onion plant parts and soil at harvest (HPLC method)

Treatment (g ha^{-1})	Field soil on 0 day	Onion plant	Onion bulb	Field soil at harvest
100	0.178	<0.01	<0.01	<0.01

Discussion

The herbicides evaluated showed differential responses influenced by dose, timing, weed spectrum, mode of action and crop selectivity. Oxyfluorfen is widely used in onion production and belongs to the pigment biosynthesis-inhibiting herbicide group. It causes chlorosis and bleaching in susceptible species (20). The selectivity of onion for oxyfluorfen was possible due to its inherent

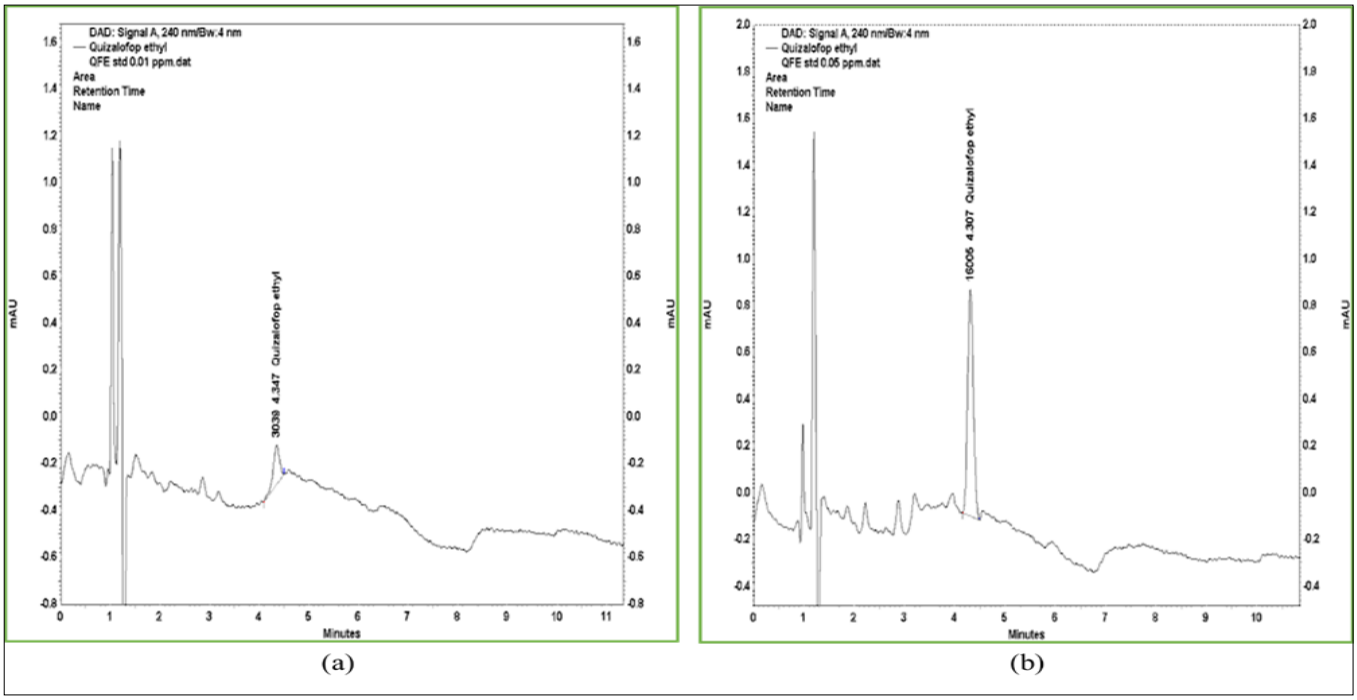

Fig. 6. Chromatograms of Oxyfluorfen + Quizalofop-ethyl standards at (a) 0.01 mg L^{-1} and (b) 0.05 mg L^{-1}.

tolerance of crops against these herbicides.

The predominant weed flora in the onion field may vary depending on several factors, including the season, previous crops, edaphic and climatic conditions, cultural practices, moisture availability and growing methods. The prominent weeds observed in the experimental site were *Cynodon dactylon*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium* and *Echinochloa colona* among grassy, *Cyperus rotundus* among sedge and *Alternanthera sessilis*, *Amaranthus viridis* and *Spilanthes acmella* among the broadleaf weeds. These weeds were mostly seasonal and appeared due to the microclimate of the crop (8, 16, 18, 31, 32).

Several research findings showed that oxyfluorfen has successfully controlled broad leaved weeds in vegetables systems including broccoli (33), onion (5), chilli pepper (34) and cauliflower (35). However, a single POST application of quizalofop-ethyl resulted in lower WCE (43.21 %) due to its selective action against grassy weeds only (3, 36, 37). The lack of early-season suppression enabled broadleaf and sedge species to dominate.

Presently oxyfluorfen 100 g a.i. ha^{-1} as PRE followed by manual weeding is the common practice in most of the onion growing ecologies in India (38, 39). However, some tracts still rely on 2 to 3 manual weedings for weed control in onion (40).

The use of a single herbicide, either PRE or POST does not control the weed growth throughout the critical period of crop weed competition. Manual weeding is labor-intensive, costly and constrained by labor shortages (3, 8).

Quizalofop-ethyl, propaquizafop belonging to fatty acid synthesis inhibitor group are only effective in controlling narrow leaved weeds, therefore yielded lower overall control in fields dominated by mixed flora. The ready-mix application of Quizalofop-ethyl + Oxyfluorfen under the study effectively controlled the wider spectrum of weeds, notably for a longer period. However, the other combination tested could not be able to control the mixed weed flora in onion.

Elucidating that Oxyfluorfen followed by Quizalofop-ethyl + Oxyfluorfen (RM) substantially reduced weed biomass relative to other treatments.

Though Oxyfluorfen as PRE controlled the early phases of germinating weeds but could not be sufficient to reduce the weed growth for a prolonged period of crop growth. Moreover, the initial period of slow crop growth coupled with tapering narrow leaf is highly susceptible to weed pressure notably for a longer period. Therefore, the present study revealed the supremacy of the herbicide mixtures (RM) of different group over the single (either PRE or POST) or PRE followed by POST (17, 18, 40).

The significant control of weed biomass of early stages by oxyfluorfen followed by the reasonable control of subsequent flushes of broad-spectrum weeds by the ready-mix application of Quizalofop-ethyl + Oxyfluorfen created a healthy microclimate for better crop growth and bulb yield.

The weed pressure significantly increases the undesirable traits of yield attributes like double / bolter production, thereby reduced the final harvested bulb yield. There existed a strong negative correlation between weed biomass with onion yield as envisaged from study. Notably, the quality of A, B & C grade bulbs are also significantly influenced by the weed biomass. The strong competition for the common inputs and space due to the weed pressure might be the cause of reduced bulb size.

Therefore, Oxyfluorfen as PRE followed by Quizalofop-ethyl + Oxyfluorfen (RM) as POST has the potential to increase WCE and significantly control weeds through enhanced herbicidal efficiency across regions. Repeated use of herbicides with the same mode of action accelerates resistance evolution (41).

Hence single use of Oxyfluorfen as PRE or Quizalofop-ethyl as POST in onion could reduce bio efficacy and fastened resistance development. Use of compatible herbicide mixtures as ready-mix as a follow up application is a suitable strategy to control weeds and delay the resistant development. The treatment demonstrates potential for wider evaluation across onion-growing agro-ecologies.

The compatible herbicide mixture under study is quite safe for the soil and environment as per the residue analysis report was within permissible residue limits, indicating environmental and crop safety under study conditions (42, 43).

Conclusion

The sequential application of Oxyfluorfen as a pre-emergence herbicide followed by Quizalofop-ethyl + Oxyfluorfen (RM) was effective and exhibited good crop selectivity in onion. Oxyfluorfen 23.5 % EC at 50 g a.i. ha^{-1} followed by a post-emergence application of Quizalofop-p-ethyl 4 % + Oxyfluorfen 6 % EC (RM) at 100 g a.i. ha^{-1} significantly reduced weed count and weed dry weight relative to the weedy check and other herbicide treatments, which resulted in a higher WCE and HEI. This treatment produced significantly higher bulb yield than manual weeding. It improved key yield attributes including polar diameter, equatorial diameter and the proportion of A and B grade bulbs. A strong correlation was observed between weed dry weight and bulb yield along with all desirable yield traits. Based on the 2-year field evaluation, the sequential use of Oxyfluorfen (PRE) followed by Quizalofop-p-ethyl + Oxyfluorfen (RM) (POST) can be recommended for effective weed management and improved bulb yield in onion under similar agro-ecological conditions.

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Authors' contributions

UP conducted the research and writing the manuscript. RD and BKM conceptualized the idea. PT and RKN helped in writing and analysis of the data. AKBM helped in statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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