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Effect of topramezone herbicide on weed suppression, crop safety and productivity in chickpea (*Cicer arietinum* L.)

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Abstract

Chickpea (*Cicer arietinum* L.) productivity is often constrained by severe weed infestation, particularly during early growth stages, necessitating efficient and safe weed management strategies. The use of post-emergence herbicides is limited due to potential crop phytotoxicity, highlighting the need for alternative options. A field trial was undertaken at Sriniketan, West Bengal, during the rabi seasons of 2021–2022 and 2022–2023 to study the performance of topramezone at different application rates as a post-emergence herbicide in chickpea cultivation. The experiment followed a randomised block design consisting of 9 treatments replicated 3 times, comparing topramezone (15–25 g ha^{-1}) with standard herbicides, pendimethalin and imazethapyr. Results revealed that application of topramezone at 25 g ha^{-1} at 25 days after sowing significantly reduced weed density and dry weight, resulting in improved crop growth and productivity. This treatment showed performance comparable to pendimethalin (750 g ha^{-1}) and superior to imazethapyr (60 g ha^{-1}). European Weed Research Council (EWRC) phytotoxicity scores for all topramezone treatments remained at one across all observation intervals, indicating no crop injury, whereas imazethapyr caused transient phytotoxicity (score up to 4 at 7 days after herbicide application) that declined by 30 days after application. Higher plant height, leaf area index, dry matter accumulation and seed yield (1402.58 kg ha^{-1}) were recorded under this treatment. The study demonstrates that topramezone at 25 g ha^{-1} can serve as an effective and safe post-emergence herbicide in chickpea cultivation.

Keywords: imazethapyr; pendimethalin; post-emergence; topramezone; weed control efficiency

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Introduction

Pulses, a subgroup of leguminous crops, are a significant supplier of dietary protein and essential for improving the soil health, combating climate change and fixing nitrogen biologically (1). India is the world's largest producer, consumer and importer of pulses, accounting for approximately 25 % of global production, 27 % of global consumption and 14 % of global imports (2). Despite its leading position in pulse production, India continues to face a gap between domestic production and demand (3). Per capita net availability of pulses declined from 51.1 g day^{-1} in 1971 to 41.9 g day^{-1} in 2013, highlighting the need to enhance pulse production and productivity (4). Pulses contain about 20–25 % protein, which is significantly higher than that of wheat and rice (5). They are also rich in dietary fibre and essential nutrients, contributing to improved digestion and cardiovascular health (6). In addition, pulses require less water compared to many other cereal crops and play an important role in food security and rural livelihoods in developing countries (7). However, pulse cultivation faces several constraints, including low productivity, pests, diseases and severe weed infestation (8). Therefore, developing effective and sustainable production technologies is essential to enhance pulse productivity.

Chickpea (*Cicer arietinum* L.), also known as Bengal gram, is a highly esteemed legume crop in India that is primarily grown under rainfed conditions (9). It is a cool season crop and grown worldwide as a food crop. India, Pakistan, Turkey, Iran, Myanmar, Mexico and Australia are the major chickpea producing countries in the world (10). It is a cost-effective and nutritionally significant source of high-quality protein for individuals who are unable to afford animal proteins or follow a predominantly vegetarian diet, as well as source of essential amino acids, minerals and fibre, beta-carotene,

calcium, phosphorus, magnesium, zinc and iron (11). Moreover, chickpea contributes to soil fertility via symbiotic nitrogen fixation (12). Under favourable growing conditions, chickpea is determined to fix nearly 60 kg nitrogen (N) ha^{-1} on average, though under optimal circumstances or in well-managed systems, greater fixation has been reported in earlier studies (13). It also has unsaturated fatty acids and carotenoids. In the Indian subcontinent, chickpeas are split (cotyledons) and made into flour (besan) which is used to make a range of foods (14). Around 20.47 g of protein, 4.31 mg of iron, 557 µg folate, 57 mg of calcium and 378 kilocalories are found in 100 g of dried chickpea on average (15). In India, chickpea occupies approximately 10.47 million hectares, producing around 12.27 million tonnes with an average productivity of 1172 kg ha^{-1}. It is projected that India will dominate the world in both production and consumption in upcoming years (16). Maharashtra occupies the largest area (28.23 % of the total area) under chickpea cultivation followed by Madhya Pradesh and Rajasthan (17). During 2020–2021 in West Bengal, chickpea was cultivated over an area of 39770 ha, yielding a total production of 50070 tonnes with an average productivity of 1259 kg ha^{-1} (18). Reduced chickpea productivity is primarily attributed to suboptimal agronomic practices, insufficient biological nitrogen fixation, seed deterioration due to various insect pests and diseases and the susceptibility of cultivars to abiotic stresses (19). Among these constraints, weed infestation is the most critical factor, as uncontrolled weed growth markedly reduces crop yield (20). In severe cases, weed competition can cause yield losses of up to 80 % in chickpea (21).

Weeds compete with crops for vital resources such as nutrients, moisture, space and light (22). Owing to its slow initial growth, chickpea is highly vulnerable to early-stage weed infestation (23). The first 30 days after sowing (DAS) constitute the critical period of crop-weed competition in chickpea (24). Severe weed infestation during this critical phase can result in yield losses ranging from 18 to 90 %, depending on environmental conditions, crop characteristics and management practices (25). Manual weeding, though effective and eco-friendly, is constrained by labour shortages, while mechanical weeding is often impractical under field conditions (26). Consequently, farmers increasingly rely on herbicides, which offer broad-spectrum efficacy, operational efficiency and lower production costs than manual or mechanical weeding, thereby improving the economic feasibility of chickpea cultivation (27).

Chemical weed control in chickpea depends heavily on pre-emergence herbicides such as pendimethalin, which provide effective early-season control but cannot address weeds emerging after the crop has established (28). Post-emergence options are considerably more limited, as chickpea is sensitive to many of the herbicides available for broad-spectrum weed control in field crops. Imazethapyr, the post-emergence herbicide most widely used in pulses, inhibits acetolactate synthase (ALS) and has been reported to cause chlorosis, stunting and growth suppression in chickpea and other grain legumes, with yield reductions persisting even after the visible symptoms subside (29, 30). This narrow and partly unsatisfactory range of post-emergence options represents a practical constraint for growers, particularly where labour shortages prevent timely manual weeding or where weather delays the pre-emergence application window. Therefore a clear need to identify post-emergence herbicides that combine broad-spectrum efficacy with reliable crop safety in chickpea. Topramezone 3-(4,5-dihydro-3-isoxazolyl)-2-methyl-4-methylsulfonylphenyl methanone offers a possible alternative (31). It was developed and registered as a post-emergence herbicide in maize, where it controls both grass and broad-leaved weeds through inhibition of 4-hydroxyphenylpyruvate dioxygenase (HPPD). The HPPD inhibition blocks plastoquinone biosynthesis and, indirectly, carotenoid synthesis, producing the characteristic photobleaching of susceptible weed shoots that precedes plant death (32). Because this mode of action differs from that of the ALS-inhibiting herbicides currently used in pulses, topramezone also offers a means of diversifying herbicide chemistry within pulse-based cropping systems. Evidence for topramezone in chickpea remains preliminary. Only a small number of studies have examined its performance in the crop and these have generally evaluated a narrow range of doses at a limited number of locations. Reported outcomes are encouraging, but they do not yet establish the dose at which effective weed suppression is achieved without risk of crop injury, nor do they include systematic assessment of phytotoxicity over time following application. Limited information is available on the performance of topramezone in chickpea grown on the lateritic soils of eastern India, where soil reaction, texture and weed flora differ appreciably from the regions in which earlier work was conducted.

The present study was therefore undertaken to evaluate topramezone as a post-emergence herbicide in chickpea under the lateritic soils of West Bengal. The specific objectives were to determine the dose at which topramezone provides effective weed suppression in chickpea, to assess whether the crop sustains any injury at these doses and whether such injury persists and to compare its performance against the pre-emergence and post-emergence herbicides currently used in the crop. The study thereby aims to establish whether topramezone can serve as an effective and crop-safe post-emergence herbicide for chickpea and to contribute to the development of sustainable weed management strategies for pulse-based systems in eastern India.

Materials and Methods

Experimental site

The present research was carried out during the rabi seasons of two consecutive years, 2021–2022 and 2022–2023, at the Agricultural Farm of Palli Siksha Bhavana, Sriniketan. The experimental site is situated in a semi-arid, sub-humid agro-climatic zone of West Bengal, at an average elevation of 58.90 m above mean sea level. Its geographic coordinates were around 23.6671° N latitude

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and 87.6617° E longitude. The experimental soil was sandy loam in texture and slightly acidic in reaction, with a pH of 5.80 and electrical conductivity (EC) of 0.15 dS m^{-1}. The soil contained 0.38 % organic carbon, 201 kg ha^{-1} available nitrogen (N), 17.21 kg ha^{-1} available phosphorus (phosphorus pentoxide (P_2O_5)) and 156.27 kg ha^{-1} available potassium (potassium oxide (K_2O)), indicating moderate fertility status.

Experimental design and treatments

The experiment was laid out in a randomised block design (RBD) comprising 9 treatments, each replicated 3 times. The treatments included T_1- topramezone 15 g ha^{-1} as post-emergence (POE); T_2- topramezone 17.5 g ha^{-1} as POE; T_3- topramezone 20 g ha^{-1} as POE; T_4- topramezone 22.5 g ha^{-1} as POE; T_5- topramezone 25 g ha^{-1} as POE; T_6- imazethapyr 60 g ha^{-1} as POE; T_7-pendimethalin 750 g ha^{-1} as pre-emergence (PE); T_8- weed free; T_9- unweeded control. The range of topramezone doses (15–25 g ha^{-1}) selected for the present study was based on available literature on its efficacy in other crops, particularly maize, along with limited preliminary evidence in pulse crops. Previous studies suggest that lower doses may not provide adequate weed control, whereas higher doses may increase the risk of crop phytotoxicity. Therefore, a graded range of doses was chosen to identify the optimum level that ensures effective weed suppression with minimal or no adverse effects on chickpea under field conditions. Since the use of topramezone in chickpea is not well established, multiple doses were evaluated to determine its optimum dose for weed control and crop safety. In contrast, imazethapyr (60 g ha^{-1}) and pendimethalin (750 g ha^{-1}) were included as standard check treatments at their recommended doses, as they are widely used for weed management in chickpea. This treatment structure enabled a benchmark comparison to assess the relative efficacy and suitability of topramezone. Additionally, T_8- weed free treatment was maintained through regular manual weeding throughout the crop growth period, whereas T_9- unweeded control was left untreated, allowing natural weed growth throughout the season.

Crop management

The field experiment was conducted in plots measuring 4.5 × 3.5 m. Following the harvest of the preceding crop, the land was prepared to obtain a fine tilth by ploughing twice with a tractor-drawn cultivator in a crosswise direction, followed by harrowing with a tractor-drawn rotavator. A basal dose of fertilisers were applied during the final land preparation at the recommended rate of 20 : 60 : 60 kg ha^{-1} of nitrogen (N), phosphorus (phosphorus pentoxide (P_2O_5)) and potassium (potassium oxide (K_2O)) respectively. Nitrogen was supplied through urea, phosphorus through single super phosphate (SSP) and potassium through muriate of potash (MOP). Chickpea seeds of variety Anuradha (WBG-39) were sown at a seed rate of 50 kg ha^{-1}, maintaining a spacing of 30 cm between rows and 10 cm between plants. Sowing was carried out in a north-south orientation to ensure uniform sunlight interception. All other recommended agronomic practices were uniformly followed across all treatments to maintain optimal crop growth and experimental consistency.

Herbicide application

The required quantity of herbicide for each treatment was calculated based on the plot area and the prescribed application rates. Herbicides were applied using a knapsack sprayer fitted with a flat-fan nozzle, maintaining a spray volume of 500 L ha^{-1} to ensure uniform coverage. Pendimethalin at 750 g ha^{-1} (T_7) was applied as a pre-emergence treatment one day after sowing. Post-emergence applications of imazethapyr (T_6) and topramezone (T_1, T_2, T_3, T_4 and T_5) were carried out at 25 days after sowing (DAS).

The required amount of herbicide for individual plots was determined using the following formula:

RQ (g or mL) = (Recommended dose (gram active ingredient ha^{-1}) × plot area (m^2))/(10000 × (percentage of active ingredient in the commercial formulation/100))

Where

RQ: required quantity of commercial formulation per plot

10000: conversion factor (m^2 in 1 hectare).

In the weed-free treatment, manual weeding was performed thrice at 25, 50 and 75 DAS to maintain the plots free of weed interference. Conversely, in the unweeded control, weeds were allowed to grow unchecked throughout the cropping season.

Observations recorded

Weed density and dry weight were assessed separately for three categories: grasses, broad-leaved weeds and sedges (the latter being absent in the experimental field). Observations were recorded at 30 and 90 DAS. At each sampling, one quadrat (0.5 × 0.5 m) was randomly placed within each plot to collect the weed samples. The weeds were identified, counted category-wise and subsequently converted into density per square metre. Weed dry weight was determined by collecting weeds category-wise, followed by washing and initial sun drying. The samples were then oven-dried at 65 °C for 72 hr until a constant weight was obtained. The dry weight of each weed category was recorded and expressed as g m^{-2}. Plant height was recorded from five randomly selected plants in each plot at 30 and 90 DAS. Measurements were taken using a measuring scale (cm) and the mean height was computed for each plot at each observation stage. At 30 and 90 DAS, leaf area per plant was recorded using a leaf area meter (LICOR model LI-3100). The leaf area index (LAI) was calculated as the ratio of leaf area per plant to the corresponding ground area.

LAI = leaf area/ground area.

Dry matter accumulation was determined at 30, 60, 90 DAS and at harvest. At each sampling stage, five representative plants were randomly selected from each plot. The samples were initially sun-dried and subsequently oven-dried at 65 °C until a constant weight

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was achieved. The dried plant material was weighed using a precision balance and dry-matter accumulation was expressed as g m^{-2}. The number of branches per plant was recorded at 75 and 90 DAS by randomly selecting representative plants from each plot. The number of branches arising from the main stem was counted manually for each selected plant and the average number of branches was calculated and expressed as number per plant. Crop growth rate (CGR) was calculated from the dry-matter accumulation recorded at successive sampling intervals. The CGR was calculated using the following equation:

$$CGR = \frac{W_2 - W_1}{t_2 - t_1}$$

Where W_1 and W_2 represent dry-matter accumulation (g $plant^{-1}$) at times t_1 and t_2 respectively and t_1 and t_2 represent the corresponding sampling times in days. The calculated dry-matter values were converted from g $plant^{-1}$ to g m^{-2} using the crop spacing and CGR was expressed as g m^{-2} day^{-1}.

Crop phytotoxicity was assessed visually at 7, 15 and 30 days after application (DAA) of herbicide using the European Weed Research Council (EWRC) scale of 1–9, where 1 = no injury and 9 = complete plant death. Any symptoms of chlorosis, necrosis, stunting, or leaf deformation were recorded for each treatment. An EWRC score of 3 or below was considered acceptable (indicating no agronomically significant injury to the crop). Weed control efficiency (WCE) was estimated based on the dry weight of weeds. The overall WCE was calculated using the total weed biomass, irrespective of species composition. It was derived from the reduction in weed dry matter in treated plots relative to the weedy check and was used as an index to evaluate the effectiveness of the herbicidal treatments. The WCE for each treatment was computed using the following formula and expressed as a percentage.

$$WCE (\%) = ((DMC - DMT)/DMC) \times 100.$$

Where, DMC is dry matter of weed (g) in unweeded control and DMT is weed dry matter (g) in a particular treatment.

At maturity, the crop from each net plot was harvested separately, followed by threshing and proper cleaning. The seed yield per net plot was recorded in kilograms and subsequently extrapolated to yield on a hectare basis (kg ha^{-1}).

Statistical analysis

Weed density and weed dry weight data were subjected to square-root transformation, $\sqrt{(x + 0.5)}$, prior to analysis in order to satisfy the assumptions of normality and homogeneity of variance. All analyses were carried out using the open-source software R (version 4.5.1). For each parameter, a combined analysis of variance (ANOVA) was first performed across the two seasons using a model comprising year, replication within year, treatment and the year × treatment interaction. The year × treatment interaction was non-significant for all measured parameters, indicating a consistent treatment response across seasons. Data from the two experimental years were therefore pooled for presentation and subsequent analysis. Homogeneity of error variance between years was examined using Bartlett's test. Where Bartlett's test was significant ($p \leq 0.05$), indicating heterogeneous error variances between years, a weighted ANOVA was performed using the reciprocal of the within-year error mean square as the weight; the parameters concerned are identified in the table footnotes. Bartlett's test was used solely to decide whether weighting was required and does not test treatment effects. The significance of treatment effects was assessed from the ANOVA *F*-test at the 5 % level and where the *F*-test was significant, treatment means were separated using Tukey's honestly significant difference (HSD) test at $p = 0.05$. Pearson's correlation coefficients were computed to evaluate the relationships between weed parameters and seed yield, with significance tested at the 5 and 1 % levels.

Results and Discussion

Weed flora

The experimental field carried a mixed flora of grasses and broad-leaved weeds in both seasons. The grasses were represented mainly by *Cynodon dactylon* (L.) Pers., *Echinochloa colona* (L.) Link and *Digitaria sanguinalis* (L.) Scop., while *Chenopodium album* L., *Gomphrena celosioides* Mart., *Ammannia baccifera* Roth, *Polygonum plebeium* R.Br. and *Vicia hirsuta* (L.) Gray were the most prominent broad-leaved species (33). Sedges were completely absent from the experimental site during both years of study. The predominance of grasses and broadleaved weeds corresponds with earlier reports that highlight the competitive pressure of *Cynodon dactylon* and *Echinochloa* spp. in pulse-based systems under lateritic soils. The absence of sedges indicates that the edaphic and microclimatic conditions of the experimental site were not conducive for their establishment (34).

Density and dry weight of weeds

At 30 DAS, significant differences were observed among the weed management treatments (Table 1). The T_7 (pendimethalin at 750 g ha^{-1} as pre-emergence) proved to be the most effective in reducing the density of both grass weeds and broadleaved weeds (BLWs). This indicates that pendimethalin, when applied at the correct dosage and timing, provides a strong residual control of weed emergence by inhibiting seed germination and early seedling growth (35). The second most effective treatment was T_5 (topramezone 25 g ha^{-1} as POE), which also demonstrated substantial efficacy in suppressing weed density, although to a slightly lesser extent than pendimethalin. These findings corroborate the results reported in previous studies (36). At 90 DAS, among the herbicide treatments, the lowest densities of grasses and broadleaved weeds were recorded in T_7 (pendimethalin 750 g ha^{-1} as PE) which was statistically on par with T_5 (topramezone 25 g ha^{-1} as POE).

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Table 1. Effect of different weed management treatments on weed density and weed dry weight at 30 and 90 DAS (pooled data over two years, 2021–22 and 2022–23)

Treatment	Weed density (√(x + 0.5) transformed, number m^{-2})						Weed dry weight (√(x + 0.5) transformed, g m^{-2})					
	30 DAS		90 DAS		30 DAS	90 DAS	30 DAS		90 DAS		30 DAS	90 DAS
	Grass	BLW	Grass	BLW	Total	Total	Grass	BLW	Grass	BLW	Total	Total
T_1	10.82^{ab}	10.63^{b}	12.08^{ab}	11.06^{ab}	15.15^{b}	16.36^{ab}	1.84^{a}	1.76^{ab}	7.19^{b}	8.27^{b}	2.45^{ab}	10.94^{b}
T_2	10.38^{abc}	10.16^{bc}	11.72^{abc}	10.32^{ab}	14.51^{b}	15.61^{ab}	1.81^{a}	1.70^{bc}	6.45^{bc}	7.48^{bc}	2.38^{abc}	9.85^{bc}
T_3	9.64^{bc}	9.66^{bcd}	10.85^{bc}	9.85^{abcd}	13.80^{bc}	14.65^{bc}	1.75^{a}	1.56^{bcd}	5.73^{c}	6.76^{cd}	2.24^{bc}	8.85^{cd}
T_4	9.07^{cd}	9.06^{cd}	10.11^{cd}	9.13^{bcd}	12.64^{c}	13.62^{bcd}	1.70^{ab}	1.42^{cd}	5.28^{cd}	6.17^{de}	2.10^{cd}	8.10^{de}
T_5	7.33^{d}	8.27^{d}	9.16^{de}	8.37^{cd}	11.08^{d}	12.39^{cd}	1.43^{b}	1.26^{d}	4.36^{de}	5.01^{ef}	1.78^{d}	6.62^{ef}
T_6	10.42^{abc}	10.25^{bc}	11.62^{abc}	10.19^{abc}	14.60^{b}	15.44^{ab}	1.83^{a}	1.61^{bc}	6.36^{bc}	7.40^{bcd}	2.33^{bc}	9.75^{bcd}
T_7	4.17^{e}	6.02^{e}	7.64^{e}	7.98^{d}	7.29^{e}	11.04^{d}	1.04^{c}	0.90^{e}	3.93^{e}	4.34^{f}	1.18^{e}	5.83^{f}
T_8	0.71^{f}	0.71^{f}	0.71^{f}	0.71^{e}	0.71^{f}	0.71^{e}	0.71^{d}	0.71^{e}	0.71^{f}	0.71^{g}	0.71^{f}	0.71^{g}
T_9	11.56^{a}	12.29^{a}	12.99^{a}	11.75^{a}	16.86^{a}	17.51^{a}	1.96^{a}	2.00^{a}	10.94^{a}	10.40^{a}	2.71^{a}	15.09^{a}
Bartlett's test (5 %)	NS	0.037	0.045	NS	NS	NS	NS	NS	NS	NS	0.028	0.01
CV (%)	12.37	8.97	8.94	11.49	10.7	11.2	9.17	11.08	12.42	10.62	9.23	10.43
Sem (±)	0.42	0.31	0.35	0.41	0.52	0.6	0.08	0.09	0.41	0.39	0.16	0.36

DAS: days after sowing; BLW: broad-leaved weeds; CV: coefficient of variation; SEm (±): standard error of the mean.

Weed density and weed dry weight data were square-root transformed as √(x + 0.5) prior to statistical analysis; means presented are transformed values.

*Conducted weighted ANOVA to address unequal variances across years, as indicated by a statistically significant result from Bartlett's test ($p \leq 0.05$); **Means that share the same letter are not significantly different based on Tukey's HSD test ($p = 0.05$).

In terms of weed dry weight, lower dry weight of grass and broadleaved weeds were found in pendimethalin 750 g ha^{-1} as PE followed by topramezone 25 g ha^{-1} as POE and were similarly effective with topramezone 22.5 g ha^{-1} as POE at 30 DAS. At 90 DAS, pendimethalin 750 g ha^{-1} as PE was the best, with T_5 (topramezone 25 g ha^{-1}) being equally effective for both categories of weeds (Table 1).

Weed control efficiency followed the same pattern as weed dry weight (Fig. 1). At 30 DAS, the highest WCE among the herbicide treatments was recorded under T_7 (pendimethalin 750 g ha^{-1} as PE, 86.0 %), followed by T_5 (topramezone 25 g ha^{-1} as POE, 59.5 %), reflecting the residual control provided by a pre-emergence application at a stage when the post-emergence treatments had been applied only five days earlier. Within the topramezone treatments, WCE increased progressively with dose from T_1 (17.0 %) to T_5 (59.5 %). By 90 DAS, this gap had narrowed considerably: T_5 recorded 79.61 % and T_7 83.30 %, indicating comparable season-long weed suppression by the two treatments. Efficiency under T_6 (imazethapyr 60 g ha^{-1} as POE) reached 25.0 % at 30 DAS and 56.0 % at 90 DAS, remaining below all topramezone doses at or above 20 g ha^{-1} at the later stage. The weed-free treatment (T_8) maintained complete weed control at both stages. These findings align with those reported in earlier studies (37).

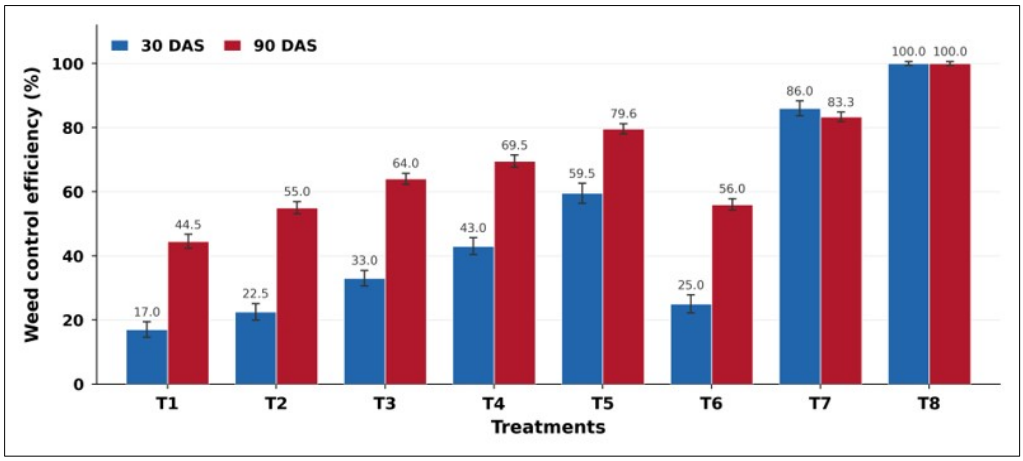


Fig. 1. Weed control efficiency (%) of different weed management treatments at 30 and 90 DAS (pooled data over two years, 2021–22 and 2022–23).

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Crop growth

Herbicidal weed management treatments significantly influenced crop growth parameters, viz., plant height, leaf area index (LAI) and dry matter accumulation (DMA) presented in Table 2, primarily due to effective suppression of weed density and biomass compared to the unweeded control (T_9). At 30 DAS, the maximum plant height was recorded under T_7 (15.37 cm), which was statistically at par with T_8 (14.24 cm), T_5 (13.97 cm) and other higher-dose treatments. The improved plant growth under these treatments can be attributed to reduced crop-weed competition, resulting in enhanced availability of nutrients, moisture and light. These results are in conformity with the findings reported in earlier studies (38). At 90 DAS, T_8 recorded the tallest plants (45.97 cm), followed by T_7 (44.97 cm) and T_5 (44.20 cm). All treatments from T_1 to T_6 were statistically at par with these, indicating that once the crop canopy had developed, differences in plant height among the weed-managed treatments were no longer significant. In contrast, the lowest plant height was recorded under the unweeded control (T_9, 32.29 cm), which was significantly shorter than every other treatment except T_1, indicating severe competition stress imposed by weeds. A comparable trend was observed for LAI. At 30 DAS, the highest LAI was recorded under T_7 and T_8 (0.39), which were statistically at par with T_5 (0.35) and T_4 (0.33). At 90 DAS, T_8 registered the maximum LAI (1.11), which was statistically at par with T_5 and T_7 (1.02 each) and with T_4 (0.86), indicating superior canopy development under these treatments.

At 30 DAS, the highest dry matter accumulation was recorded in T_7 (pendimethalin 750 g ha^{-1} as PE, 34.05 g m^{-2}), reflecting the residual weed control provided from one day after sowing, followed by T_8 (weed free, 31.93 g m^{-2}). Among the post-emergence topramezone treatments, T_5 (25 g ha^{-1} as POE) recorded the highest value (28.55 g m^{-2}), followed by T_4 (22.5 g ha^{-1}, 27.71 g m^{-2}) and T_3 (20 g ha^{-1}, 26.84 g m^{-2}). Differences among the topramezone doses were not statistically significant at this stage, which is consistent with the post-emergence treatments having been applied only 5 days earlier, at 25 DAS. The lowest dry matter accumulation was recorded under the unweeded control (T_9, 23.18 g m^{-2}).

At 60 DAS, the weed-free treatment (T_8) recorded the highest dry matter accumulation (90.07 g m^{-2}), which was statistically at par with T_7 (pendimethalin 750 g ha^{-1} as PE, 85.75 g m^{-2}) and T_5 (topramezone 25 g ha^{-1} as POE, 80.63 g m^{-2}). At 90 DAS and at harvest, T_8 recorded significantly higher dry matter (177.14 and 306.51 g m^{-2}) than all other treatments. Among the herbicide treatments, T_7 recorded the highest values at both stages (145.43 g m^{-2} at 90 DAS and 254.24 g m^{-2} at harvest) and was statistically at par with T_5 (143.04 and 250.23 g m^{-2}), indicating that the highest tested dose of topramezone sustained biomass accumulation as effectively as the pre-emergence standard. Treatment T_4 (topramezone 22.5 g ha^{-1} as POE) recorded 126.85 g m^{-2} at 90 DAS and 212.59 g m^{-2} at harvest. At harvest it was statistically at par with both T_5 and T_3 and significantly higher than T_1, T_2 and T_6. Treatment T_6 (imazethapyr 60 g ha^{-1} as POE) recorded 115.56 g m^{-2} at 90 DAS and 178.43 g m^{-2} at harvest, which was significantly above the unweeded control (T_9, 89.03 and 136.58 g m^{-2}) but significantly below T_5 at both stages.

Table 2. Effect of different weed management treatments on plant height (cm), leaf area index (LAI) at 30 and 90 DAS and dry matter accumulation (g m^{-2}) at 30, 60, 90 DAS and harvest (pooled data over two years, 2021–22 and 2022–23)

Treatment	Plant height (cm)		LAI		Dry matter accumulation (g m^{-2})			
	30 DAS	90 DAS	30 DAS	90 DAS	30 DAS	60 DAS	90 DAS	Harvest
T_1	12.23^{bc}	38.99^{ab}	0.29^{bc}	0.75^{c}	25.04^{c}	55.42^{cd}	100.72^{de}	168.46^{de}
T_2	13.03^{abc}	39.93^{a}	0.30^{bc}	0.78^{bc}	26.07^{bc}	58.82^{bcd}	109.57^{cde}	178.49^{cde}
T_3	13.14^{abc}	42.12^{a}	0.32^{bc}	0.81^{bc}	26.84^{bc}	64.89^{bc}	119.78^{cd}	193.21^{cd}
T_4	13.35^{abc}	43.28^{a}	0.33^{abc}	0.86^{abc}	27.71^{abc}	68.27^{b}	126.85^{bc}	212.59^{bc}
T_5	13.97^{ab}	44.20^{a}	0.35^{ab}	1.02^{ab}	28.55^{abc}	80.63^{a}	143.04^{b}	250.23^{b}
T_6	12.36^{bc}	40.63^{a}	0.30^{bc}	0.77^{bc}	26.99^{bc}	64.94^{bc}	115.56^{cd}	178.43^{cde}
T_7	15.37^{a}	44.97^{a}	0.39^{a}	1.02^{ab}	34.05^{a}	85.75^{a}	145.43^{b}	254.24^{b}
T_8	14.24^{ab}	45.97^{a}	0.39^{a}	1.11^{a}	31.93^{ab}	90.07^{a}	177.14^{a}	306.51^{a}
T_9	11.32^{c}	32.29^{b}	0.28^{c}	0.64^{c}	23.18^{c}	48.31^{d}	89.03^{e}	136.58^{e}
Bartlett's test (5 %)	0.003	0.003	NS	NS	NS	0.003	< 0.001	NS
CV (%)	9.38	9.40	10.91	15.90	11.93	8.68	9.2	10.95
Sem (±)	0.51	1.59	0.015	0.056	1.35	2.43	4.7	9.33

*Conducted weighted ANOVA to address unequal variances across years, as indicated by a statistically significant result from Bartlett's test ($p \leq 0.05$).

**Means that share the same letter are not significantly different based on Tukey's HSD test ($p = 0.05$).

CV: coefficient of variation; SEm (±): standard error of the mean; NS: Not significant.

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Herbicidal weed control treatments exerted a significant influence on crop growth rate (CGR) as presented in Fig. 2. During the 30 to 60 DAS period, the highest CGR was recorded in T_8 (1.94 g m^{-2} day^{-1}), which was statistically at par with T_5 (1.74 g m^{-2} day^{-1}) and T_7 (1.72 g m^{-2} day^{-1}), while significantly outperforming the remaining treatments. In the 60 to 90 DAS interval, T_8 recorded the highest CGR (2.90 g m^{-2} day^{-1}), followed by T_5 (2.08 g m^{-2} day^{-1}) and T_7 (1.99 g m^{-2} day^{-1}). Treatment T_8 was significantly superior to all other treatments, while T_5 and T_7 were significantly higher than T_9 (1.36 g m^{-2} day^{-1}), highlighting the continued benefit of herbicidal treatments in promoting vigorous vegetative growth. From 90 DAS to harvest, CGR reached its highest values of the season across all treatments. Treatment T_8 again recorded the maximum (4.15 g m^{-2} day^{-1}), followed by T_5 (3.48 g m^{-2} day^{-1}) and T_7 (3.55 g m^{-2} day^{-1}), while the lowest value was recorded in T_9 (1.52 g m^{-2} day^{-1}). The consistently higher CGR under effective weed management across all three intervals reflected the sustained advantage of reduced crop-weed competition throughout the crop cycle.

The number of branches per plant differed significantly among the treatments at both 75 and 90 DAS (Table 3). The highest number was recorded under T_8 (weed free), with 10.44 and 11.82 branches $plant^{-1}$ at 75 and 90 DAS respectively. Among the herbicide treatments, T_7 (pendimethalin 750 g ha^{-1} as PE) recorded the highest values (9.36 and 10.67 branches $plant^{-1}$) and was statistically at par with T_5 (topramezone 25 g ha^{-1} as POE, 8.76 and 10.59 branches $plant^{-1}$) at both stages. Branch number increased progressively with increasing topramezone dose from T_1 to T_5. Treatment T_4 (topramezone 22.5 g ha^{-1} as POE) recorded 8.08 and 9.16 branches $plant^{-1}$, which was statistically at par with both T_5 and T_3 but significantly higher than T_1 and T_2. Treatment T_6 (imazethapyr 60 g ha^{-1} as POE) recorded 6.59 and 7.09 branches $plant^{-1}$, significantly lower than T_5 at both stages. It exceeded the unweeded control significantly at 75 DAS, although the difference was not significant at 90 DAS. The lowest branch number throughout was recorded under T_9 (4.53 and 5.46 branches $plant^{-1}$).

Table 3. Effect of weed management treatments on number of branches per plant at 75 and 90 DAS (pooled data over two years, 2021–22 and 2022–23)

Treatment	Number of branches per plant	
	75 DAS	90 DAS
T_1	5.33^{ef}	6.37^{de}
T_2	6.08^{de}	6.82^{de}
T_3	6.82^{cd}	7.90^{cd}
T_4	8.08^{bc}	9.16^{bc}
T_5	8.76^{b}	10.59^{ab}
T_6	6.59^{de}	7.09^{de}
T_7	9.36^{ab}	10.67^{ab}
T_8	10.44^{a}	11.82^{a}
T_9	4.53^{f}	5.46^{e}
Bartlett's test (5 %)	< 0.001	0.02
CV (%)	10.48	11.91
Sem (±)	0.31	0.41

*Conducted weighted ANOVA to address unequal variances across years, as indicated by a statistically significant result from Bartlett's test ($p \leq 0.05$).

**Means that share the same letter are not significantly different based on Tukey's HSD test ($p = 0.05$).

CV: coefficient of variation; SEm (±): standard error of the mean.

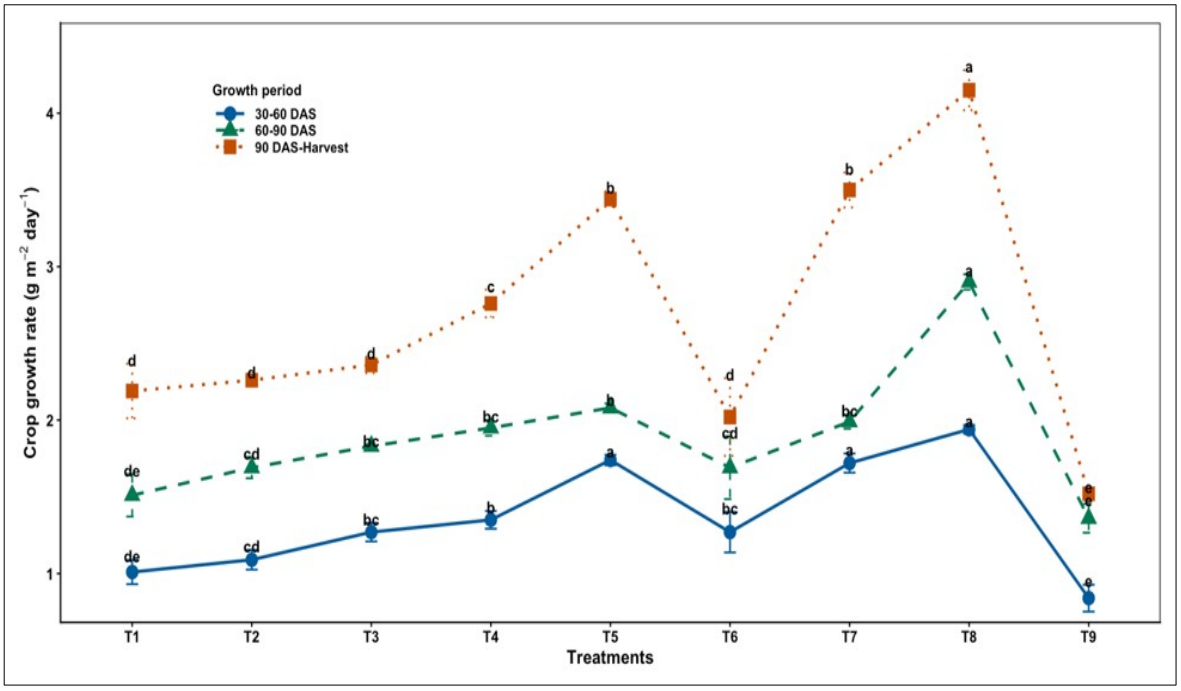


Fig. 2. Crop growth rate (g m^{-2} day^{-1}) of chickpea under different weed management treatments at various growth stages (pooled data over two years, 2021–22 and 2022–23).

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Crop phytotoxicity

Crop phytotoxicity scores assessed using the EWRC scale (1–9) at 7, 15 and 30 days after herbicide application (DAA) are presented in Table 4. All topramezone treatments (T_1–T_5) recorded an EWRC score of 1 at all 3 observation intervals, indicating complete absence of phytotoxic symptoms throughout the evaluation period. No chlorosis, necrosis, stunting, or leaf deformation was observed in any of the topramezone-treated plots, irrespective of the dose applied (15–25 g ha^{-1}). Similarly, pendimethalin (T_7), being a pre-emergence herbicide applied before crop emergence, did not cause any post-emergence contact injury and the weed-free (T_8) and unweeded control (T_9) plots also recorded a score of 1, as no herbicide was applied. These findings confirm that topramezone, across all evaluated doses, is safe for use in chickpea and poses no risk of crop injury under field conditions, corroborating earlier reports (37), of the absence of phytotoxic effects of post-emergence herbicides in chickpea when applied at recommended doses. In contrast, imazethapyr (T_6) recorded an EWRC score of 4 at 7 DAA, indicating moderate phytotoxic injury characterised by visible chlorosis and stunted growth. By 15 DAA, the score declined to 3, reflecting partial but incomplete recovery of the affected plants. At 30 DAA, the score further declined to 2, indicating that most visible symptoms had subsided. However, the persistent yield reduction observed in T_6 (919.53 kg ha^{-1}) compared to T_5 (1402.58 kg ha^{-1}) suggests that even after apparent visual recovery, sub-lethal physiological damage continued to suppress crop productivity. This finding is consistent with some earlier studies (39), which reported that imazethapyr-induced phytotoxicity in chickpea, while transient in visual expression, can cause significant and lasting reductions in yield-contributing parameters. The differential phytotoxicity response between topramezone and imazethapyr further underscores the agronomic suitability of topramezone as a safer post-emergence herbicide option for chickpea, in line with comparative phytotoxicity assessments reported for other HPPD- and ALS-inhibiting herbicides in legume crops.

Seed yield and stover yield

Seed yield was significantly influenced by the weed management treatments (Fig. 3). The highest seed yield was recorded under T_8 (weed free, 1567.57 kg ha^{-1}), which was statistically at par with T_5 (topramezone 25 g ha^{-1} as POE, 1402.58 kg ha^{-1}) and T_7 (pendimethalin 750 g ha^{-1} as PE, 1348.47 kg ha^{-1}) but significantly superior to all remaining treatments. Among the herbicide treatments, T_5 recorded the highest seed yield and was statistically at par with T_7, indicating that a single post-emergence application of topramezone at 25 g ha^{-1} achieved productivity comparable to both the pre-emergence standard and season-long manual weeding. This performance may be attributed to sustained weed suppression during the critical period of crop-weed competition, which improved resource availability, branching and reproductive development (36). Seed yield under T_5 was significantly higher than under the lower topramezone doses T_4 (22.5 g ha^{-1}, 1147.93 kg ha^{-1}), T_3 (20 g ha^{-1}, 972.43 kg ha^{-1}), T_2 (17.5 g ha^{-1}, 785.15 kg ha^{-1}) and T_1 (15 g ha^{-1}, 628.29 kg ha^{-1}), indicating a clear dose-dependent response within the range evaluated (40). Treatment T_6 (imazethapyr 60 g ha^{-1} as POE) recorded 919.53 kg ha^{-1}, which was statistically at par with T_3 but significantly lower than T_5. The reduced yield under T_6 was associated with the transient phytotoxicity recorded at 7 DAA (Table 4), comprising chlorosis and stunted growth that restricted plant development, mirroring the imazethapyr-induced chlorosis and growth suppression reported in chickpea and lentil. The unweeded control (T_9) recorded the lowest seed yield (448.46 kg ha^{-1}), 71.4 % below the weed-free treatment, underlining the severity of unchecked weed competition.

Stover yield followed a comparable pattern (Fig. 3). The highest stover yield was recorded under T_8 (3001.08 kg ha^{-1}), reflecting the cumulative benefit of season-long weed-free conditions on total biomass production. Among the herbicide treatments, T_5 recorded the highest stover yield (2699.09 kg ha^{-1}), which was statistically at par with both T_7 (2641.43 kg ha^{-1}) and T_8, indicating that topramezone at 25 g ha^{-1} supported vegetative biomass as effectively as the pre-emergence standard and as manual weeding. Stover yield declined progressively with decreasing topramezone dose, from T_4 (2339.55 kg ha^{-1}) through T_3 (2052.11 kg ha^{-1}) and T_2 (1755.60 kg ha^{-1}) to T_1 (1487.71 kg ha^{-1}). Treatment T_6 recorded 1960.77 kg ha^{-1}, statistically at par with T_3 and T_2 but significantly below T_5. The lowest stover yield was recorded under T_9 (1223.22 kg ha^{-1}) (41). The absence of a significant difference between a post-emergence application of topramezone and the pre-emergence standard indicates that topramezone at 25 g ha^{-1} offers an equally effective alternative where post-emergence control is required.

Table 4. Crop phytotoxicity scores (EWRC scale, 1–9) of chickpea under different weed management treatments at 7, 15 and 30 days after herbicide application (DAA) (pooled over two years, 2021–22 and 2022–23)

Treatment	7 DAA	15 DAA	30 DAA
T_1: Topramezone 15 g ha^{-1} as POE	1	1	1
T_2: Topramezone 17.5 g ha^{-1} as POE	1	1	1
T_3: Topramezone 20 g ha^{-1} as POE	1	1	1
T_4: Topramezone 22.5 g ha^{-1} as POE	1	1	1
T_5: Topramezone 25 g ha^{-1} as POE	1	1	1
T_6: Imazethapyr 60 g ha^{-1} as POE	4	3	2
T_7: Pendimethalin 750 g ha^{-1} as PE	1	1	1
T_8: Weed free	1	1	1
T_9: Unweeded control	1	1	1

DAA: days after herbicide application; EWRC: European Weed Research Council; POE: post-emergence; PE: pre-emergence.

Scale 1: no injury, Scale 9: complete plant death. Score ≤ 3 considered agronomically acceptable.

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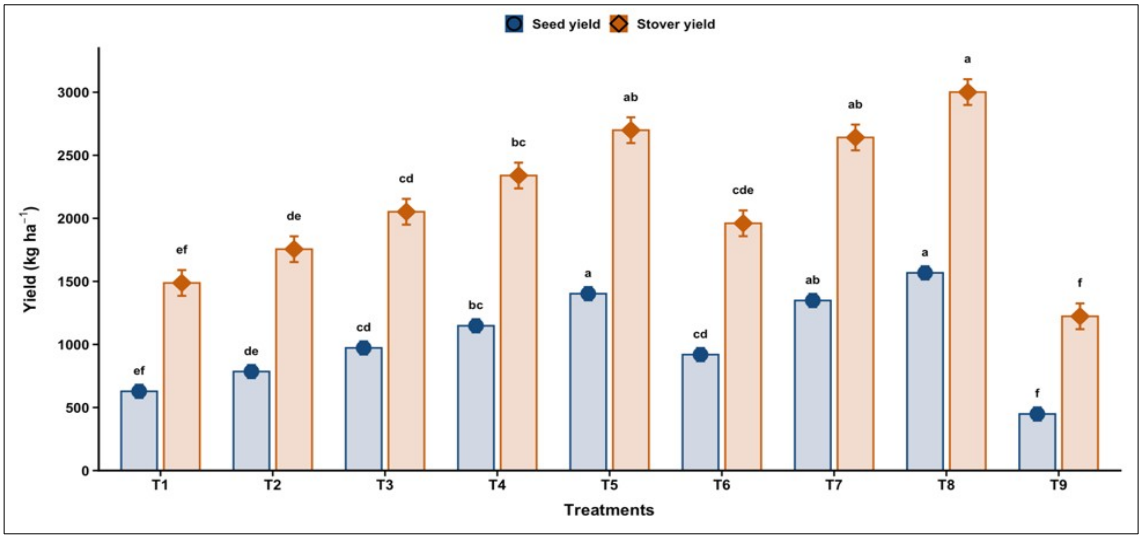


Fig. 3. Effect of different weed management treatments on seed yield and stover yield (kg ha^{-1}) of chickpea (pooled over two years, 2021–22 and 2022–23).

Error bars denote SEm. Within each yield component, means sharing the same letter are not significantly different by Tukey's HSD test (p = 0.05). Seed yield: Sem (±) 51.96, CV (%) 12.42 %, Bartlett's test p = 0.27. Stover yield: Sem (±) 102.18, CV 11.76 %, Bartlett's test p = 0.84.

Pearson's correlation between different weed parameters and yield

Pearson's correlation analysis revealed a highly significant (p < 0.01) negative relationship between seed yield and the measured weed parameters, as illustrated in Fig. 4. This indicates that greater weed infestation was associated with a marked reduction in seed yield. Among the measured weed parameters, broadleaf weed density showed the weakest negative correlation with seed yield (r = -0.72**), although the relationship remained highly significant. The remaining weed parameters also showed significant negative associations with seed yield, indicating that greater weed infestation was consistently associated with reduced crop productivity. Furthermore, all weed parameters were highly significantly and positively intercorrelated, indicating that increases in one weed parameter were generally associated with increases in the other weed parameters. These relationships demonstrate the close association between weed infestation and reduced seed yield; however, the correlation analysis does not establish causality.

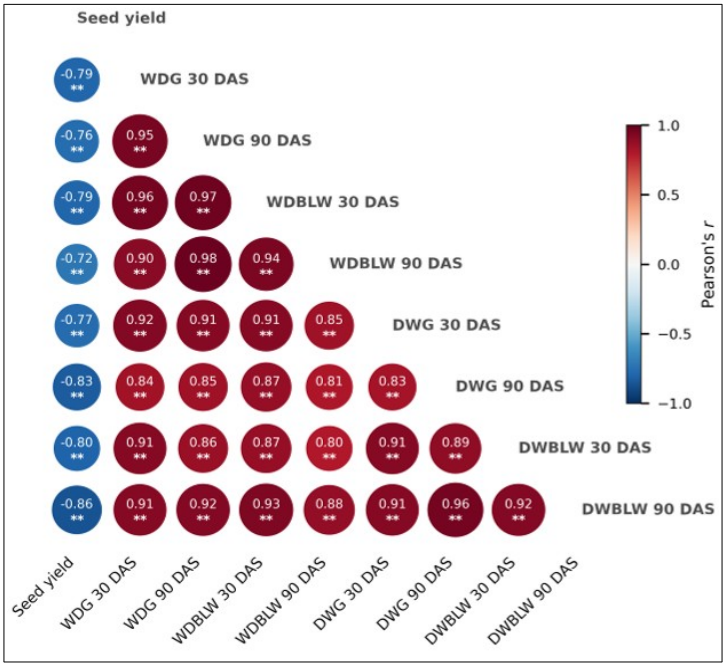


Fig. 4. Pearson's correlation coefficients between weed parameters and seed yield of chickpea (pooled over two years, 2021–22 and 2022–23).

WDG: weed density of grasses (no. m^{-2}); WDBLW: weed density of broad-leaved weeds (no. m^{-2}); DWG: dry weight of grasses (g m^{-2}); DWBLW: dry weight of broad-leaved weeds (g m^{-2}); DAS: days after sowing. Weed density and dry weight data were square-root transformed as √(x + 0.5) prior to analysis. *Indicates significance at the 5 % level (p < 0.05) and ** at the 1 % level (p < 0.01).

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Conclusion

Post-emergence application of topramezone at 25 g ha^{-1} at 25 days after sowing (DAS) was the most effective of the doses tested, reducing weed density and dry weight and producing the highest seed and stover yields among the herbicide treatments (1402.58 and 2699.09 kg ha^{-1} respectively). Its performance was statistically at par with pre-emergence pendimethalin (750 g ha^{-1}) and with the weed-free control and superior to imazethapyr (60 g ha^{-1}). All topramezone doses (15–25 g ha^{-1}) recorded European Weed Research Council (EWRC) score of 1 at 7, 15 and 30 days after application (DAA), indicating the absence of visible crop injury throughout the assessment period, whereas imazethapyr caused transient injury (score 4 at 7 DAA, declining to 2 at 30 DAA) accompanied by a persistent yield penalty. Topramezone at 25 g ha^{-1} can therefore be recommended as an effective and selective post-emergence herbicide for chickpea, offering growers a viable option where the pre-emergence window has been missed or where labour constraints preclude timely manual weeding. As the findings derive from a single location over two seasons, multi-location validation and assessment of herbicide residue dynamics are warranted before wider recommendation. Future work should also examine the integration of topramezone within integrated and precision weed management frameworks to support more sustainable weed control in chickpea.

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Authors' contributions

MSR and PG conceived and designed the field experiment. MSR conducted the field trial, collected the data and performed the laboratory and data analyses. MK contributed to weed identification, data curation and interpretation of the results. KAS carried out the statistical analysis of the experimental data. GS contributed to manuscript review. PG supervised the study, secured resources and critically reviewed the manuscript. MSR prepared the original draft of the manuscript. All authors have 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

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly solely for grammar, spelling and punctuation correction at the final editing stage. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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