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Effect of Different Herbicides on Rainfed Maize (*Zea mays* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. Author SRM designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors LND and VHB managed the analyses of the study. Author MRK managed the literature searchesAll authors read and approved the final manuscript.

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Abstract

A field experiment was conducted as part of an M.Sc. research programme to investigate the effect of different herbicides on rainfed maize (*Zea mays* L.) during the kharif (rainy) season of 2022 at the Department of Agriculture, Swami Vivekanand University, Sagar. The experiment comprised eight weed-management treatments: T_1, topramezone at 25 g ha^{-1} applied at 20 days after sowing (DAS); T_2, atrazine at 1.25 kg ha^{-1} applied at 20 DAS; T_3, 2,4-D sodium salt at 1.0 kg ha^{-1} applied at 20 DAS; T_4, topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} applied as a tank mixture at 20 DAS; T_5, topramezone at 12.5 g ha^{-1} + 2,4-D sodium salt at 500 g ha^{-1} applied as a tank mixture at 20 DAS; T_6, the recommended weed-management practice comprising pre-emergence application of atrazine at 1.25 kg ha^{-1} + IC + HW; T_7, weed-free treatment; and T_8, weedy check. The experiment was laid out in a randomised complete block design (RCBD) with three replications. The effects of the herbicidal treatments on the growth, yield attributes, and productivity of maize were evaluated. The principal growth parameters assessed included plant height (cm) and leaf area per plant (cm^2), while the yield attributes and yield parameters included grain weight per cob (g), 100-seed weight (g), grain yield (kg ha^{-1}), and stover yield (t ha^{-1}). Among the herbicidal treatments, the application of topramezone

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at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} as a tank mixture resulted in significantly greater plant height at all recorded growth stages. Grain yield was also significantly influenced by the herbicide treatments. The tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} produced the highest grain yield (6,791 kg ha^{-1}), followed by the tank mixture of topramezone at 12.5 g ha^{-1} + 2,4-D sodium salt at 500 g ha^{-1} (6,609 kg ha^{-1}). Both tank-mixture treatments produced higher grain yields than the corresponding individual herbicide applications. Similarly, the highest stover yield (9.39 t ha^{-1}) was recorded with the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1}. This treatment was statistically at par with topramezone at 12.5 g ha^{-1} + 2,4-D sodium salt at 500 g ha^{-1}, which recorded a stover yield of 8.71 t ha^{-1}. Both tank-mixture treatments performed better than the individual herbicide applications with respect to stover production. In contrast, the lowest stover yield (7.00 t ha^{-1}) was recorded under the weedy-check treatment. Overall, the results indicated that the tank-mixture application of topramezone with atrazine, as well as topramezone with 2,4-D sodium salt, was more effective in improving the growth and yield performance of rainfed maize than the respective sole herbicide applications under the conditions of the present experiment.

Keywords: Early post-emergence; herbicides; rainfed maize; Weed management.

1. Introduction

By 2050, the world is expected to undergo substantial demographic, climatic and resource-related changes. The global population is projected to exceed 9 billion, while the average global temperature is anticipated to increase, placing additional pressure on essential resources such as food, fodder and fuel (Fan & Brzeska, 2010; Indian Institute of Maize Research, 2015). These challenges are particularly relevant to developing countries such as India, where population growth continues to increase the demand for food production. If the prevailing rate of population growth persists, India may require approximately 301 million tonnes of food grains by 2050, as estimated by the National Academy of Agricultural Sciences (Sankaran *et al*., 2005). Consequently, increasing agricultural productivity through efficient and sustainable crop-management practices will be essential to meet future food requirements.

Maize (*Zea mays* L.) is one of the most important cereal crops cultivated in India and plays a significant role in the country's agricultural economy. In India, maize is cultivated over an area of approximately 8.78 million ha, with an annual production of about 21.76 million tonnes. The average productivity of maize in the country is approximately 2,478 kg ha^{-1}, which is considerably lower than the world average of 4,860 kg ha^{-1} (Indian Institute of Maize Research, 2015). This productivity gap highlights the considerable scope for improving maize production through better crop-management practices. Maize contributes substantially to food and nutritional security and also serves as an important source of livestock feed and industrial raw materials. In recent years, maize oil has gained popularity because of its favourable composition and absence of cholesterol. Furthermore, several maize-derived products, including corn starch, corn flakes, gluten, germ cake, lactic acid, alcohol and acetone, are either consumed directly as food products or used as raw materials in industries such as paper, textiles and fermentation. Globally, approximately two-thirds of total maize production is utilised for livestock feed or for the commercial production of starch and oil (Khalil & Jan, 2002). Thus, maize has considerable importance not only as a food and feed crop but also as an industrial commodity.

Despite its economic importance, the production and productivity of maize are substantially affected by weed infestation. Weeds compete with maize plants for essential growth resources, including nutrients, soil moisture, sunlight and space, particularly during the vegetative phase and the early stages of reproductive development. Severe weed competition during these critical growth periods may adversely affect crop growth, yield attributes and ultimately grain productivity. Therefore, effective and timely weed management is essential for achieving the yield potential of maize. The use of early post-emergence herbicides may provide a practical and effective alternative to conventional weed-control methods. Early post-emergence weed management may involve the application of either a single herbicide or a combination of two compatible herbicides. However, the use of a well-planned tank mixture of herbicides can potentially provide more effective and consistent weed suppression than the application of a single post-emergence herbicide. Such combinations may broaden the spectrum of weed control by simultaneously targeting different groups of weeds, including broad-leaved and grassy weed species. Therefore, appropriate tank-mixture combinations of early post-emergence herbicides may offer an effective strategy for improving weed control, reducing crop–weed competition and enhancing the growth and productivity of maize.

Recent field investigations have reported that pre- and post-emergence herbicides used sequentially or in compatible combinations can reduce weed interference and support maize growth and yield, with performance varying among herbicide programmes and application schedules (Alptekin et al., 2023; Shukla et al., 2023; Singh et al., 2024; Sivamurugan et al., 2024; Lema et al., 2025; Kumar et al., 2026; Ali et al., 2026). Accordingly, a research gap remains in the comparative evaluation of the specific early post-emergence tank mixtures examined in this study under rainfed maize conditions, particularly across crop growth, yield attributes, weed index, nitrogen uptake and economic performance. Therefore, the objective of the present investigation was to evaluate the effect of different herbicides, including sole and tank-mixture early post-emergence applications, on the performance of rainfed maize (*Zea mays* L.).

2. Materials and Methods

A field experiment for M.Sc. students was conducted at the Department of Agriculture, Swami Vivekanand University, Sagar, during kharif (rainy season) 2022 to study the effect of early post-emergence herbicides on the performance of rainfed maize. The experiment was conducted on black clayey soil (Vertisols). Composite soil samples were collected from the experimental site before sowing and were analysed for various physical and chemical characteristics. The soil pH was 7.5, and the soil was medium in available nitrogen, phosphorus and potassium. The experiment was laid out in a randomised complete block design (RCBD) with

three replications. The experimental details were as follows: spacing, 60 x 20 cm; sowing season, Kharif, 2022; fertiliser, 100:50:25 N:PO:K_2O kg ha-1; gross plot size, 4.5 m x 4.2 m; net plot size, 3.6m x 3.2 m; genotype, 900-M Gold; and seed rate, 25 kg ha-1.

2.1 Application of Herbicides

The required amount of herbicide for each experimental treatment was calculated using the following formula.

$$F = \frac{R \times 100}{\text{Purity (\%)}} \times \frac{A}{10{,}000}$$

Where:

F = Formulated product required in kg or lit ha-^{1}.
R=kg a.i. ha^{-1} to be sprayed (recommended rate)
A = Area to be sprayed (m^2)

Thus, the calculated amount of herbicide was sprayed in each treatment using a knapsack sprayer with a spray volume of 750 litres of water per hectare.

Pre-emergence application of herbicide: The pre-emergence herbicide (Atrazine) was sprayed in T after sowing the crop. The pre-emergence application was made uniformly on the soil surface using 750 litres of spray solution with minimal trampling.

Post-emergence application of herbicides: Post-emergence herbicides were applied uniformly to the weeds at 15 DAS according to the treatments, using 750 litres of spray solution.

Chart 1. Treatment Details and treatment combinations are as follows

Treatment
T_1 - Topramezone (25g / ha) at 20 DAS (Early post-emergence)
T_2 - Atrazine (1.25kg / ha) at 20 DAS (Early post-emergence)
T_3 - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)
T_4 - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)
T_5 - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)
T_6 - Atrazine (PRE) 1.25kg / ha + lC + HW)
T_7 - Weed free
T_8 - Weedy check

Five plants from the sampling area were randomly selected, and observations on the following growth and yield parameters were recorded at 30, 60 and 90 DAS and at harvest: plant height (cm), leaf area per plant (dm^2), grain weight per cob (g), hundred-seed weight (g), grain yield (kg ha^{-1}) and stover yield (ha^{-1}).

2.2 Plant Height (cm)

Plant height was recorded from five representative plants in each treatment. Before cob emergence, plant height was measured from the base of the plant to the tip of the fully opened uppermost leaf. Following tasselling, plant height was measured from the base of the plant to the collar of the flag leaf. The mean plant height was calculated and expressed in centimetres (cm).

2.3 Leaf Area per Plant (dm^2)

Leaf area per plant was estimated using five representative plants from each treatment. The maximum length and breadth of the leaves were measured, and their product was multiplied by the total number of green leaves present on each plant. A correction factor of 0.75 was subsequently applied to estimate the total leaf area per plant, following the method described by Stickler *et al.* (1961). The leaf area was calculated using the following relationship:

$$\text{Leaf area per plant} = \text{Maximum leaf length} \times \text{Maximum leaf breadth} \times \text{Number of green leaves per plant} \times 0.75$$

The calculated leaf area was expressed in square decimetres (dm^2) per plant.

2.4 Yield Components and Yield

At harvest, the cobs obtained from the five plants previously selected for recording growth observations were used for the determination of yield attributes. The following yield components and yield parameters were recorded.

2.4.1 Grain Weight per Cob (g)

The cobs collected from five randomly selected plants were sun-dried and subsequently shelled. The grains obtained from each cob were weighed separately, and the mean value was calculated. The average grain weight was expressed as grain weight per cob in grams (g).

2.4.2 Hundred-Seed Weight (g)

A representative grain sample was collected from the net plot yield of each treatment. From this sample, 100 seeds were randomly counted and weighed using an appropriate weighing balance. The recorded weight was expressed as 100-seed weight in grams (g).

2.4.3 Grain Yield (kg ha^{-1})

At physiological maturity, the cobs were harvested and dehusked separately for each treatment. The harvested cobs were air-dried and subsequently shelled. The grains obtained after shelling were thoroughly cleaned and weighed for each net plot. The plot-wise grain yield was then converted to a hectare basis and expressed in the appropriate yield unit.

2.4.4 Stover Yield (t ha^{-1})

After harvesting the cobs, the remaining maize stalks from each net plot were allowed to dry completely under sunlight. The dried stover from each plot was weighed separately, and the corresponding stover yield was calculated on a hectare basis. The values were expressed as tonnes per hectare (t ha^{-1}).

2.5 Nitrogen Uptake by Weeds and Maize Plants

Representative weed and maize plant samples were collected at 30 and 60 days after sowing (DAS) for the determination of nitrogen uptake. The collected samples were oven-dried to obtain a constant dry weight and subsequently ground using a Wiley mill. The ground plant material was passed through a 2-mm sieve to obtain a uniform sample. These prepared samples were then used for the estimation of nitrogen concentration in weeds and maize plants.

2.5.1 Nitrogen (N)

The nitrogen content of the weed and maize plant samples was determined using the Modified Micro-Kjeldahl method as described by Jackson (1967). The nitrogen concentration in the plant material was expressed as a percentage. Total nitrogen uptake was calculated using the nitrogen concentration and the corresponding dry-matter accumulation of weeds or maize plants and was expressed as kg ha^{-1}. The nitrogen uptake was calculated using the following relationship:

$$\text{Nitrogen uptake (kg ha}^{-1}\text{)} = \text{Nitrogen content (\%)} \times \text{Dry-matter yield (kg ha}^{-1}\text{)} / 100$$

This procedure was followed separately for weed and maize plant samples to assess the influence of different weed-management treatments on nitrogen utilisation by the crop and associated weeds.

2.6 Economics

The prices of the inputs and the market price of the maize crop prevailing at the time of their use were used to calculate the cost of cultivation and economic returns.

Net income (Ra) Gross income (ha Cost of cultivation (ha) Benefit:

The cost ratio was calculated as follows:

$$\text{Cost ratio} = \frac{\text{ross income (ha}^{-1}\text{) Benifit}}{\text{Cost of cultivation (ha}^{-1}\text{)}}$$

2.7 Transformation of Data

Data on weed count and weed dry weight showed a high degree of variation. A relationship between the mean and variance was observed. Therefore, the data on weed count and weed dry weight were subjected to (x + 0.5) transformation to make the analysis of variance more valid, as suggested by Bartlett (1947).

2.8 Statistical Analysis of Data

The data collected from the experiment were analysed statistically following the procedure as described by Gomez and Gomez (1984). The level of significance used in the 'F' test was P = 0.05. Critical difference values were calculated wherever the 'F' test was significant.

3. Results

3.1 Plant Height

The statistically analysed data pertaining to plant height of maize at different growth stages are presented in Table 1. Plant height varied significantly among the weed-management treatments at most stages of crop growth, although no significant differences were observed among the treatments at 30 days after sowing (DAS). This indicated that the influence of weed competition and weed-management practices on plant height was not pronounced during the initial stage of crop growth. At 60 DAS, the weed-free treatment recorded the greatest plant height (175.53 cm). However, it was statistically at par with the application of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (174.55 cm), the recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} + IC + HW (174.49 cm), topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (168.00 cm), topramezone alone at 25 g ha^{-1} (166.87 cm), 2,4-D alone at 1.0 kg ha^{-1} (164.72 cm), and atrazine alone at 1.25 kg ha^{-1} (164.60 cm). In contrast, the weedy check recorded significantly shorter plants (150.07 cm), indicating the adverse effect of uninterrupted weed competition on maize growth. At 90 DAS, the recommended weed-management practice of atrazine at 1.25 kg ha^{-1} + IC + HW recorded a plant height of 193.05 cm, followed by the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (192.00 cm), topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (189.26 cm), and atrazine at 1.25 kg ha^{-1} (175.53 cm). These treatments recorded significantly greater plant height and were statistically at par with the weed-free treatment, which produced the greatest numerical plant height of 197.97 cm. A similar trend was observed at harvest. The weed-free treatment recorded the tallest plants (204.63 cm) and was statistically at par with topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (199.40 cm), the recommended practice of atrazine at 1.25 kg ha^{-1} + IC + HW (196.75 cm), and topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (191.60 cm). The significantly lowest plant height at harvest was recorded in the weedy check (169.30 cm). The greater plant height observed under the weed-free treatment and effective herbicidal treatments may be attributed to reduced crop–weed competition for essential growth resources such as nutrients, soil moisture, light and space. Effective suppression of weeds during the critical stages of crop growth might have enabled maize plants to utilise available resources more efficiently, thereby promoting better vegetative growth and plant development. Conversely, the reduced plant height recorded under the weedy check could be associated with prolonged competition from weeds throughout the crop-growing period. The present findings are in agreement with those reported by Srividya *et al.* (2011). Similarly, Shinde *et al.* (2001) and Shekhawat and Gautam (2002) reported higher values for growth parameters under weed-free conditions, followed by treatments involving two hand weedings, further demonstrating the beneficial effects of effective weed management on maize growth.

Table 1. Plant height of maize (cm) as influenced by weed management treatments in maize

Treatment	30 DAS	60DAS	90DAS	At harvest
T_1 - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	36.18	166.87	170.53	177.03
T_2 - Atrazine(1.25kg / ha) at 20 DAS (Early post-emergence)	39.19	164.60	175.53	184.26
T_3 - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	38.68	164.72	171.68	182.27
T_4 - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	42.62	174.55	192.00	199.40
T_5 - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	37.11	168.00	189.26	191.60
T_6 - Atrazine (PRE) 1.25kg / ha + lC + HW)	45.11	174.49	193.05	196.75
T_7 - Weed free	46.30	175.53	197.97	204.63
T_8 - Weedy check	35.64	150.07	157.13	169.30
Sem +_	4.23	3.93	8.61	5.428
C.D.(0.5)	12.84	11.91	26.12	16.464

IC: Inter-cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

3.2 Leaf Area

The statistically analysed data on leaf area of maize at different growth stages are presented in Table 2. Leaf area recorded at 60 and 90 days after sowing (DAS) and at harvest was significantly influenced by the different weed-management treatments. However, at 30 DAS, the differences in leaf area among the treatments were non-significant, indicating that the effects of weed competition and weed-management practices were not sufficiently pronounced during the early stage of crop growth. At 60 DAS, the recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} + IC + HW recorded a leaf area of 73.28 dm^2, while the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} recorded 73.11 dm^2. These treatments produced significantly greater leaf area and were statistically at par with the weed-free treatment, which recorded the highest numerical value of 77.72 dm^2. In contrast, the weedy check recorded a significantly lower leaf area of 49.07 dm^2. The sole applications of topramezone, atrazine and 2,4-D recorded leaf areas of 60.67, 55.81 and 59.31 dm^2, respectively, and were significantly inferior to the tank-mixture treatments. At 90 DAS, the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} produced a significantly greater leaf area of 77.27 dm^2 and was statistically at par with the recommended weed-management practice of atrazine at 1.25 kg ha^{-1} + IC + HW, which recorded 81.14 dm^2. Similarly, the application of topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} resulted in a leaf area of 73.06 dm^2 and was statistically at par with the topramezone + atrazine tank-mixture treatment. In comparison, the sole applications of atrazine at 1.25 kg ha^{-1}, topramezone at 25 g ha^{-1} and 2,4-D at 1.0 kg ha^{-1} recorded significantly lower leaf areas of 71.45, 70.03 and 67.43 dm^2, respectively. The lowest leaf area at this stage was observed in the weedy check (58.63 dm^2). A trend similar to that observed at 90 DAS was also evident at harvest, demonstrating the sustained advantage of effective weed-management practices in maintaining greater photosynthetic leaf area throughout the later stages of crop growth. The greater leaf area under the weed-free, recommended weed-management and tank-mixture treatments may be attributed to effective suppression of weeds and the

consequent reduction in competition for nutrients, soil moisture, solar radiation and space. Improved availability of these resources may have facilitated greater leaf expansion and maintenance of a more productive crop canopy. Conversely, persistent weed competition in the weedy check restricted vegetative development and resulted in a marked reduction in leaf area. These findings are in conformity with those reported by Hawaldar *and Agasimani* (2012), Haji *et al.* (2012) and Nadiger (2011). Total dry-matter production (TDMP) in maize is strongly influenced by important growth attributes such as leaf area (LA). Leaf area and the associated leaf area index (LAI) are widely regarded as important indicators of crop growth because they influence assimilatory capacity and transpiration. An adequately developed leaf canopy enhances the interception of solar radiation and canopy photosynthesis, thereby contributing to improved dry-matter accumulation and ultimately to higher maize productivity (Duncan, 1975).

Table 2. Leaf area (cm) at different growth stages of maize as influenced by weed management treatments in maize

Treatment	30 DAS	60DAS	90DAS	At harvest
T 1 - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	18.50	60.77	70.03	33.09
T 2 - Atrazine (1.25kg / ha) at 20 DAS (Early post-emergence)	19.52	55.81	71.45	35.14
T 3 - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	17.57	59.31	67.43	31.27
T 4 - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	23.48	73.11	77.27	39.89
T 5 - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	21.82	67.22	73.06	35.57
T 6 - Atrazine (PRE) 1.25kg / ha + lC + HW)	23.91	73.28	81.14	37.29
T 7 - Weed free	25.93	77.72	85.14	45.89
T 8 - Weedy check	13.07	49.07	58.63	27.04
Sem +_	2.19	1.59	1.54	1.69
C.D.(0.5)	7.21	4.82	4.658	5.12

IC: Inter-cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

3.3 Yield and Yield Components of Maize

The observations on grain weight per plant, hundred-grain weight, grain yield and stover yield are presented in Table 3.

3.4 Grain Weight (g plant^{-1})

The statistically analysed data on grain weight per plant are presented in Table 3. Grain weight per plant was significantly influenced by the different weed-management treatments. The weed-free treatment recorded the highest grain weight per plant (164.14 g plant^{-1}), which was significantly superior to most of the other treatments. However, it was statistically at par with the recommended weed-management practice (145.16 g plant^{-1}) and the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (144.43 g plant^{-1}). These latter two treatments were also statistically comparable with each other. In contrast, the weedy check recorded the significantly lowest grain weight per plant (80.06 g plant^{-1}). The reduction in grain weight under the weedy condition may be attributed to severe and prolonged competition between maize and weeds for essential growth resources, particularly nutrients, soil moisture, light and space. Effective weed suppression under the weed-free, recommended weed-management and tank-mixture treatments likely improved resource availability to the crop, thereby promoting better assimilate production and translocation towards developing grains. The present findings are in conformity with those reported by Walia *et al.* (2007), who also observed improved yield attributes of maize under effective weed-management practices.

Table 3. Hundred-grain weight (g) of maize as influenced by weed management treatments in maize

Treatment	100 seed weight (g)	Grain weight (g plant^{-1})
T 1 - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	24.58	117.21
T 2 - Atrazine (1.25kg / ha) at 20 DAS (Early post-emergence)	25.82	118.12
T 3 - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	23.45	116.55
T 4 - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	29.38	144.43
T 5 - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	28.2	127.82
T 6 - Atrazine (PRE) 1.25kg / ha + lC + HW)	30.26	145.16
T 7 - Weed free	33.19	164.14
T 8 - Weedy check	19.12	80.06
Sem +_	2.14	7.6
C.D.(0.5)	6.49	23.04

IC: Inter-cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

3.5 Hundred Grain Weight (g)

The statistically analysed data on hundred-grain weight are presented in Table 3. Hundred-grain weight differed significantly among the various weed-management treatments. The weed-free treatment recorded the highest hundred-grain weight (33.19 g). The

recommended weed-management practice comprising atrazine at 1.25 kg ha⁻¹ + IC + HW, the tank mixture of topramezone at 12.5 g ha⁻¹ + atrazine at 625 g ha⁻¹, and topramezone at 12.5 g ha⁻¹ + 2,4-D sodium salt at 500 g ha⁻¹ applied at 20 DAS also produced comparatively higher hundred-grain weights and were statistically at par with the weed-free treatment. Among these treatments, the tank mixture of topramezone at 12.5 g ha⁻¹ + 2,4-D sodium salt at 500 g ha⁻¹ recorded a hundred-grain weight of 28.20 g. In comparison, the sole application of atrazine at 1.25 kg ha⁻¹ at 20 DAS recorded a hundred-grain weight of 25.82 g. This was followed by the sole applications of topramezone and 2,4-D, which recorded hundred-grain weights of 24.58 and 23.45 g, respectively. These values were lower than those obtained with the tank-mixture treatments, indicating the relative advantage of combined herbicide application in improving this important yield attribute. The significantly lowest hundred-grain weight (19.12 g) was recorded under the weedy-check treatment. The reduction in grain weight under continuous weed infestation may be attributed to intense crop–weed competition for nutrients, moisture, light and other growth resources, which might have restricted photosynthate production and its subsequent translocation to developing grains. Conversely, effective weed suppression under the weed-free, recommended weed-management and tank-mixture treatments may have improved resource availability and assimilate partitioning towards grain development, thereby resulting in heavier grains. These findings are in conformity with those reported by Walia *et al.* (2007), who similarly observed improvement in grain weight under effective weed-management practices.

3.6 Grain Yield of Maize (kg ha^{-1})

The statistically analysed data on grain yield of maize are presented in Table 4. Grain yield was significantly influenced by the different weed-management treatments. The recommended weed-management practice comprising atrazine at 1.25 kg ha⁻¹ + IC + HW recorded a grain yield of 6,882 kg ha⁻¹. Similarly, the tank mixtures of topramezone at 12.5 g ha⁻¹ + atrazine at 625 g ha⁻¹ and topramezone at 12.5 g ha⁻¹ + 2,4-D at 500 g ha⁻¹ produced grain yields of 6,791 and 6,609 kg ha⁻¹, respectively. These treatments recorded significantly higher grain yields and were statistically at par with the weed-free treatment, which produced the highest grain yield of 7,103 kg ha⁻¹. In comparison, the sole applications of topramezone, atrazine and 2,4-D (T_1, T_2 and T_3, respectively) recorded comparatively lower grain yields than the recommended weed-management practice and the tank-mixture treatments. This indicates that the combined application of compatible herbicides was more effective in improving maize productivity than their individual applications, presumably because of more efficient and broad-spectrum weed suppression during the critical period of crop growth. The significantly lowest grain yield was recorded under the weedy-check treatment (4,973 kg ha⁻¹), which was inferior to all other weed-management treatments. The substantial reduction in grain yield under continuous weed infestation may be attributed to severe crop–weed competition for essential growth resources such as nutrients, soil moisture, light and space. Such competition adversely affects vegetative growth, dry-matter accumulation and yield-contributing characters, ultimately resulting in reduced grain productivity. Conversely, effective weed suppression under the weed-free treatment, recommended weed-management practice and herbicide tank mixtures may have improved the availability and utilisation of growth resources by maize plants. This probably favoured better crop growth, enhanced photosynthetic efficiency and improved translocation of assimilates towards developing grains, thereby contributing to higher grain yield. These findings are in conformity with those reported by Srividya *et al.* (2011), who also observed higher maize grain yield under effective weed-management practices.

3.7 Stover Yield (t ha $^{-1}$)

Table 4. Grain yield (kg ha-1), stover yield (t ha-1), and weed index (%) of maize as influenced by weed management treatments

Treatment	Grain yield (kg ha^{-1})	Stover yield (t ha^{-1})	Weed index (%)
T_1 - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	5707	8.58	19.39
T_2 – Atrazine (1.25kg / ha) at 20 DAS (Early post-emergence)	5713	8.80	19.33
T_3 - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	5604	8.41	20.89
T_4 - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	6791	9.39	4.38
T_5 - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	6609	8.70	7.05
T_6 - Atrazine (PRE) 1.25kg / ha + lC + HW)	6882	9.66	3.19
T_7 - Weed free	7103	9.70	-
T_8 - Weedy check	4973	7.00	29.86
Sem +_	278	0.48	1.94
C.D.(0.5)	842	1.48	5.89

IC: Inter-cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

The statistically analysed data on stover yield of maize are presented in Table 4. Stover yield was significantly influenced by the different weed-management treatments. The weed-free treatment recorded the highest stover yield (9.70 t ha⁻¹) and was significantly superior to most of the other treatments. Among the weed-management treatments, the recommended weed-management practice comprising atrazine at 1.25 kg ha⁻¹ + IC + HW at 30 DAS recorded a stover yield of 9.66 t ha⁻¹. This was followed by the tank mixture of topramezone at 12.5 g ha⁻¹ + atrazine at 625 g ha⁻¹ (9.39 t ha⁻¹), atrazine at 1.25 kg ha⁻¹ (8.81 t ha⁻¹), topramezone at 12.5 g ha⁻¹ + 2,4-D at 500 g ha⁻¹ (8.71 t ha⁻¹), topramezone at 25 g ha⁻¹ (8.58 t ha⁻¹), and 2,4-D at 1.0 kg ha⁻¹ (8.42 t ha⁻¹). These weed-management treatments were statistically at par with one another with respect to stover yield. In contrast, the weedy-check treatment recorded the significantly lowest stover yield (7.00 t ha⁻¹) compared with the remaining treatments. The reduction in stover yield under the weedy check may be attributed to prolonged crop–weed competition for essential growth resources, including nutrients, soil moisture, light and space. Such competition restricts vegetative growth and dry-matter accumulation, thereby reducing the

production of maize stover. The comparatively higher stover yield recorded under the weed-free treatment, recommended weed-management practice and herbicide tank-mixture treatments may be associated with effective suppression of weeds and improved availability of growth resources to the maize crop. Reduced weed interference probably promoted better plant growth, leaf development and overall dry-matter accumulation, ultimately resulting in greater stover production. These findings are in conformity with those reported by Walia *et al.* (2007) and Bijanzadeh and Ghadiri (2006), who similarly observed improved yield attributes and biomass production under effective weed-management practices. Conversely, the weedy-check treatment recorded the lowest values for yield components, further demonstrating the detrimental effect of unchecked weed competition on maize productivity.

3.8 Weed Index

The statistically analysed data pertaining to the weed index are presented in Table 4. The weed index differed significantly among the various weed-management treatments. A significantly lower weed index was recorded with the recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} + IC + HW at 30 DAS (3.19%) and the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (4.38%). These treatments were statistically at par with the weed-free treatment, indicating their greater effectiveness in minimising yield losses caused by weed interference. In contrast, the weedy-check treatment recorded the significantly highest weed index (29.86%). The greater weed index under the weedy check was primarily associated with the considerable reduction in maize grain yield caused by uninterrupted weed growth. Under such conditions, weeds competed intensively with the crop for essential growth resources, including nutrients, soil moisture, light and space, resulting in poorer crop growth and reduced expression of yield-contributing characters. Similar observations regarding yield reductions under severe weed competition were reported by Krishnamurthy *et al.* (1981). The relatively low weed index observed under the recommended weed-management practice and the topramezone + atrazine tank mixture further indicates that effective weed suppression during the critical period of crop–weed competition can substantially reduce yield losses and enable the crop to utilise available resources more efficiently.

3.9 Nutrient Uptake by Maize (kg ha^{-1})

The data on nitrogen uptake by maize at 30 and 60 DAS are presented in Table 5. Nitrogen uptake was significantly influenced by the different weed-management treatments at both stages of crop growth, indicating that effective weed control considerably affected nutrient acquisition by maize.

At 30 DAS, the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1}, applied at 20 DAS, recorded a comparatively high nitrogen uptake of approximately 9.40 kg ha^{-1}. This treatment was statistically at par with the recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} + IC + HW (9.56 kg ha^{-1}) and the weed-free treatment (9.88 kg ha^{-1}). The weed-free treatment recorded the highest numerical nitrogen uptake at this stage. Nitrogen uptake was comparatively lower in the treatment receiving the tank mixture of topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}. Similarly, the sole applications of topramezone at 25 g ha^{-1}, atrazine at 1.25 kg ha^{-1} and 2,4-D at 1.0 kg ha^{-1} recorded nitrogen uptakes of 6.69, 6.23 and 5.00 kg ha^{-1}, respectively. These values were lower than those obtained with the more effective tank-mixture and recommended weed-management treatments. A trend broadly similar to that observed at 30 DAS was also recorded at 60 DAS. The greater nitrogen uptake under the weed-free, recommended weed-management and effective tank-mixture treatments may be attributed to reduced competition from weeds for available soil nitrogen and other growth resources. Improved weed suppression probably promoted greater crop growth, dry-matter accumulation and root development, thereby enhancing the capacity of maize plants to absorb and utilise available nitrogen. Conversely, greater weed competition under less effective weed-management treatments may have reduced the quantity of nutrients available for crop uptake. Soil biological activity and nutrient transformation are also closely associated with the biochemical functioning of the soil. Soil enzyme activity is widely used as an indicator of soil biological activity because it responds to variations in the physical, chemical, microbiological and biochemical properties of soil (Burns, 1978; McLaren, 1975). Soil enzymes play an important role in several nutrient-cycling processes and are considered useful indicators of changes resulting from soil and crop-management practices because of their relatively rapid response and ease of measurement (Dick, 1994, 1997; Bandick & Dick, 1999).

Table 5. Nitrogen uptake by maize plant (kg ha^{-1}) at 30 DAS and 60 DAS as influenced by weed management treatments in maize

Treatment	Nitrogen uptake	
	30 DAS	60DAS
T $_1$ - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	6.69	32.46
T $_2$ - Atrazine (1.25 kg / ha) at 20 DAS (Early post-emergence)	6.23	35.50
T $_3$ - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	5.00	31.69
T $_4$ - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	9.40	45.60
T $_5$ - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	7.71	40.36
T $_6$ - Atrazine (PRE) 1.25kg / ha + lC + HW)	9.34	47.33
T $_7$ - Weed free	9.88	53.14
T $_8$ - Weedy check	4.27	28.26
Sem +_	0.565	2.36
C.D.(0.5)	1.71	7.17

IC: Inter cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

3.10 Economics

The data on gross returns, cost of cultivation, net returns and benefit:cost ratio as influenced by the different weed-management treatments are presented in Table 6. These results are in conformity with the findings of Patel *et al.* (2006).

3.11 Cost of Cultivation (ha^{-1})

The highest cost of cultivation was recorded in the weed-free check (Rs. 37352ha^{-1}). The cost of cultivation was also higher with the sole application of topramezone at 25 g/ha (Rs. 33084ha^{-1}), the recommended weed-management practice (Rs. 32774 ha^{-1}), and the tank mixtures of topramezone at 12.5 g/ha + atrazine at 625 g/ha (Rs.32429ha^{-1}) and topramezone at 12.5 g/ha + 2,4-D at 500 g/ha (Rs. 31867 ha^{-1}). Among the herbicide treatments, the cost of cultivation was lower with the sole application of 2,4-D Na salt at 1.0 kg/ha (Rs. 28749ha^{-1}) than with all other herbicide treatments. Shukla et al. (2023) also reported the economic advantage of combined herbicide application in maize.

Table 6. Economics of maize as influenced by weed management treatments

Treatment	Cost of cultivation (ha^{-1})	Gross returns (ha^{-1})	Net return (ha^{-1})	B: C ratio
T $_1$ - Topramezone (25g / ha) at 20 DAS (Early post-emergence)	33084	113127	80043	3.42
T $_2$ - Atrazine(1.25kg / ha) at 20 DAS (Early post-emergence)	29574	114536	84962	3.87
T $_3$ - 2 4-D Na salt (1kg / ha) at 20 DAS (Early post-emergence)	28749	111016	82267	3.86
T $_4$ - Topramezone (12.5g / ha) + Atrazine (625g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	32429	129688	97259	4.00
T $_5$ - Topramezone (12.5g / ha) + 2 4-D Na salt (500g / ha) at 20 DAS (Early post-emergence) (Tank mixture)	31867	123607	91740	3.88
T $_6$ - Atrazine (PRE) 1.25kg / ha + lC + HW)	32774	132309	**99535**	4.04
T $_7$ - Weed free	**37352**	**134936**	97584	3.61
T $_8$ - Weedy check	**27252**	**975714**	**68462**	3.51
Sem +_	-	3495	3275	0.15
C.D.(0.5)	-	10601	9935	0.47

IC: Inter-cultivation, HW: Hand Weeding, DAS: Days after sowing, PRE: Pre- emergence herbicide,

4. Discussion

4.1 Crop Growth and Yield of Maize as Influenced by Weed Management Practices

At 30 and 60 days after sowing (DAS), the application of herbicide tank mixtures, namely topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} and topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}, resulted in significantly lower densities of broad-leaved weeds, grassy weeds and sedges, as well as lower total weed dry matter. These treatments were statistically at par with the recommended weed-management practice. In contrast, the weedy-check treatment recorded significantly greater weed density, demonstrating the adverse consequences of allowing weeds to grow unchecked throughout the crop-growth period. Among the herbicidal treatments, the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} provided effective weed suppression and recorded a low weed index of 4.38%. This treatment was statistically comparable with the recommended weed-management practice comprising pre-emergence application of atrazine at 1.25 kg ha^{-1} followed by one hand weeding (HW) and one intercultivation (IC), which recorded a weed index of 3.19%. The tank mixture of topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} also recorded a comparatively low weed index of 7.05%. At both 30 and 60 DAS, the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} recorded significantly higher weed-control indices (WCI) of 75.99 and 86.11%, respectively. These values were statistically at par with those obtained with topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}, which recorded WCI values of 70.11 and 79.24% at 30 and 60 DAS, respectively. Similarly, the recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} followed by one hand weeding and one intercultivation recorded WCI values of 77.69 and 88.36% at the corresponding growth stages. These results indicate that the tank mixtures were comparable with the recommended weed-management practice in suppressing weed growth.

At 30 DAS, total weed density per 0.5 m² was significantly reduced by the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (8.67 weeds 0.5 m^{-2}), topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (11.67 weeds 0.5 m^{-2}), and the recommended weed-management practice (10.00 weeds 0.5 m^{-2}). These treatments were statistically at par with one another. At 60 DAS, the treatment receiving topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} recorded a comparatively low total weed density of 16.00 weeds 0.5 m^{-2} and was statistically comparable with the recommended weed-management practice, which recorded 14.67 weeds 0.5 m^{-2}. The tank mixture of topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} recorded 22.00 weeds 0.5 m^{-2} and ranked next in effectiveness. In general, the densities of grassy weeds, broad-leaved weeds and sedges, as well as total weed dry-matter accumulation, were either significantly lower under the herbicide tank-mixture treatments than under their respective sole applications or were statistically comparable with them. This suggests that the combined use of herbicides broadened the spectrum of weed control and provided more consistent suppression of the diverse weed flora present in the maize crop. Nitrogen uptake by weeds was significantly reduced by the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1}, which recorded nitrogen uptakes of 1.92 and 2.97 kg ha^{-1} at 30 and 60 DAS, respectively. These values were statistically at par with those obtained with topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}, which recorded nitrogen uptakes of 2.38 and 3.29 kg ha^{-1} at 30 and 60 DAS,

respectively. The weed-free treatment recorded the lowest nutrient uptake by weeds, with values of 1.19 and 1.56 kg ha^{-1} at 30 and 60 DAS, respectively, and was significantly lower than the other weed-management treatments. The reduced nitrogen removal by weeds under effective weed-control treatments indicates that a greater proportion of the available soil nitrogen remained accessible to the maize crop, thereby potentially contributing to improved crop growth and productivity.

Plant height was generally greater under effective weed-management treatments. The tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} consistently produced comparatively taller maize plants across the recorded growth stages. The treatment comprising topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} was the next most effective treatment, and the two tank-mixture treatments were statistically comparable at the relevant growth stages. In contrast, the weedy check consistently recorded shorter plants, reflecting the adverse effects of persistent weed competition for nutrients, moisture, light and space. The improvement in crop growth under the tank-mixture treatments can be attributed to effective suppression of competing weed flora, which facilitated greater availability of essential growth resources to maize plants. Reduced weed interference consequently favoured better vegetative development and improved the overall competitive ability of the crop.

Grain weight per plant was significantly influenced by the weed-management treatments. The recommended weed-management practice comprising atrazine at 1.25 kg ha^{-1} followed by one hand weeding and one intercultivation recorded a grain weight of 145.16 g plant^{-1}, while the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} recorded 144.43 g plant^{-1}. Both treatments were statistically at par with the weed-free treatment. The significantly lowest grain weight per plant was recorded under the weedy check (80.06 g plant^{-1}). The reduction in grain weight under uncontrolled weed infestation may be attributed to intense competition for growth resources, which restricted crop growth, assimilate production and the subsequent translocation of photosynthates towards grain development.

Grain yield was significantly greater with the tank mixtures of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (6,791 kg ha^{-1}) and topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (6,609 kg ha^{-1}) than with their respective sole herbicide applications. These two tank-mixture treatments were statistically at par with the recommended weed-management practice (6,882 kg ha^{-1}) and the weed-free treatment (7,103 kg ha^{-1}). In contrast, the weedy check recorded the significantly lowest grain yield of 4,973 kg ha^{-1}. The higher grain yield under the tank-mixture treatments may be attributed to their broader and more effective control of the weed flora, resulting in reduced crop–weed competition and improved utilisation of nutrients, water, light and space by maize plants. The favourable crop-growth environment created by efficient weed management consequently improved yield-contributing characters and final grain productivity. Stover yield followed a broadly similar pattern. The tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} recorded a stover yield of 9.39 t ha^{-1} and was statistically at par with topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}, which recorded 8.71 t ha^{-1}. These tank-mixture treatments performed favourably compared with the sole applications of the herbicides. The weedy check recorded the lowest stover yield (7.00 t ha^{-1}), indicating that continuous weed interference adversely affected vegetative growth and total biomass accumulation.

4.2 Weed Index

The weed index was significantly lower with the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (4.38%). This treatment was statistically at par with topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (7.05%) and the recommended weed-management practice (3.19%). In contrast, markedly higher weed indices were recorded with the sole applications of topramezone at 25 g ha^{-1} (19.39%), atrazine at 1.25 kg ha^{-1} (19.33%) and 2,4-D at 1.0 kg ha^{-1} (20.89%). The comparatively low weed index under the tank-mixture treatments demonstrates their effectiveness in minimising yield losses associated with weed competition. The superior performance of these combinations over the respective sole herbicide applications further suggests that the use of herbicides with complementary spectra of activity may provide more effective control of mixed weed populations in maize. Nitrogen uptake by the maize crop was also significantly influenced by the weed-management treatments. The treatments receiving topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1}, topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1}, and the recommended weed-management practice were statistically at par with one another with respect to crop nitrogen uptake. The greater nitrogen uptake observed under these treatments may be attributed to effective weed suppression, which reduced nutrient removal by weeds and consequently increased the availability of nitrogen to maize plants. Improved crop growth and dry-matter accumulation under these treatments may also have contributed to greater nutrient absorption. In contrast, nitrogen uptake by the maize crop was significantly lower under the weedy-check treatment, owing to intense competition from uncontrolled weeds for available soil nutrients. Overall, the results demonstrate that the tank mixture of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} was one of the most effective herbicidal treatments for controlling a broad spectrum of weeds, reducing weed dry matter and nutrient depletion, improving crop growth and nutrient uptake, and enhancing grain and stover yields. The tank mixture of topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} also performed favourably and was generally comparable with the recommended weed-management practice. These findings emphasise the potential advantage of appropriate herbicide tank mixtures over sole herbicide applications for effective weed management and improved productivity of maize.

4.3 Economics

The weed-free check recorded significantly higher gross returns (Rs. 134936 ha-^{1}) and was on par with topramezone 12.5 g / ha + atrazine 625 g/ha (Rs. 129688 ha-^{1}) and topramezone 12.5 g/ha + 2,4-D 500 g/ha (Rs. 123607 ha^{-1}). The same trend was observed for net returns and the B:C ratio. Topramezone 12.5 g/ha + atrazine 625 g/ha recorded higher net returns (Rs. 97259 ha-1) and was on par with topramezone 12.5 g/ha + 2,4-D 500 g/ha (Rs. 91740 ha^{-1}), which, in turn, was on par with the recommended weed-management practice (Rs. 99535ha-^{1}) and the weed-free treatment (Rs. 97584 ha^{-1}).

The benefit-cost ratio was higher with treatments receiving topramezone 12.5 g/ha + atrazine 625 g/ha (4.00), topramezone 12.5 g/ha + 2,4-D (3.88) and the recommended weed-management practice (4.04), and these treatments were on par with each other. The lower B:C ratio was recorded with the application of topramezone 25 kg/ha alone (3.42) because of lower net returns, which, in turn, resulted from significantly lower grain yield and a higher cost of cultivation.

5. Conclusions

Under the rainfed conditions of this single field experiment, effective weed management improved maize growth and productivity relative to the weedy check. The weed-free treatment produced the highest grain yield (7,103 kg ha^{-1}), while the recommended practice (6,882 kg ha^{-1}) and the tank mixtures of topramezone at 12.5 g ha^{-1} + atrazine at 625 g ha^{-1} (6,791 kg ha^{-1}) and topramezone at 12.5 g ha^{-1} + 2,4-D at 500 g ha^{-1} (6,609 kg ha^{-1}) produced comparable high yields. Among the herbicide tank mixtures, topramezone + atrazine showed the stronger overall performance, with a weed index of 4.38%, stover yield of 9.39 t ha^{-1}, maize nitrogen uptake of 45.60 kg ha^{-1} at 60 DAS and a benefit:cost ratio of 4.00. The recommended weed-management practice recorded a weed index of 3.19% and the highest benefit:cost ratio of 4.04. The weedy check had the lowest grain yield (4,973 kg ha^{-1}) and a weed index of 29.86%. These results support the potential of the evaluated tank mixtures, particularly topramezone + atrazine, as effective weed-management options for rainfed maize under the study conditions.

6. Limitations

This study was conducted during one kharif season at a single location under rainfed conditions. Consequently, the relative performance of the herbicide treatments reflects the soil, weather and weed-flora conditions prevailing during the experiment. Treatment responses may differ across seasons, locations and rainfed production environments. Multi-season and multi-location evaluations would therefore be useful to assess the consistency of weed control, crop response, nutrient uptake, yield and economic performance of the evaluated herbicide programmes.

7. Need of the Study

Information on such herbicide combinations or mixtures is not available. Therefore, intensive studies are needed to evaluate the efficacy of early post-emergence herbicides and herbicide mixtures for weed management in rainfed maize **(***Zea mays L***.).**

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Declaration of AI Use

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

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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