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RESEARCH PAPER

Effect of VLCFA, ALS and 4-HPPD inhibitors on weeds, yields and economics of *kharif* hybrid maize (*Zea mays* L.) in Varanasi

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Abstract: A field experiment was conducted during the *kharif* season of 2023–24 at Banaras Hindu University, Varanasi, India, to evaluate the effect of VLCFA (very-long-chain fatty acid inhibitors), ALS (acetolactate synthase inhibitors), and 4-HPPD (4-hydroxyphenylpyruvate dioxygenase inhibitors) herbicides, along with integrated weed management strategies, on weed suppression, crop yields and economic in *kharif* maize. The experiment followed a randomized block design with twelve treatments and three replications. Among the treatments, pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS recorded the lower weed density (3.32, 2.40 and 2.19 /m^2), dry weight (1.03, 1.94 and 1.01) of grasses, sedges and broad leaved weeds, respectively and weed index (4%) while achieving 96% weed control efficiency. This treatment notably improved number of leaves per plant, leaf area index, chlorophyll content at 50 DAS, leading to higher grain (5.61 t/ha) and stover yields (8.14 t/ha), outperforming atrazine-based treatments, which provided moderate weed suppression, while raising concerns about herbicide resistance. Economic analysis revealed that pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS had the higher net return (120742 Rs./ha) and benefit-cost (B:C) ratio (2.7), making it the most profitable weed management strategy. The study concludes that application of pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS, offer effective, sustainable, and economically viable weed control in *Kharif* maize under Varanasi's agro-climatic conditions.

Keywords: Atrazine • Herbicide resistance • Integrated weed management • *Kharif* maize • Pyroxasulfone • Weed control efficiency

Introduction

Maize (*Zea mays* L.), often referred to as the "queen of cereals," is a globally significant crop due to its high yield potential and diverse applications in food, feed, fodder, and biofuel industries (Bamboriya *et al.*, 2020). Cultivated across 193 million hectares in 170 countries, maize production reached approximately 1.2 billion metric tonnes in 2021, with the United States, China, Brazil, and India being the leading producers. While the United States records maize productivity exceeding 10 t ha^{-1}, India lags significantly behind, with an average productivity of 2.96 t ha^{-1}, which is half the global average (Anonymous, 2025). Among several factors limiting maize productivity in India, weed infestation remains a critical challenge, particularly due to the slow initial growth, wide row spacing, and frequent rainfall during the rainy season, which create a favorable environment for weed proliferation. Weeds compete with maize for light, nutrients, moisture, and space, affecting crop morphology, phenology, and grain quality while increasing harvesting

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difficulties and production costs. In extreme cases, unchecked weed growth can cause yield losses of up to 90%, depending on weed species and density. Crop yield loss was recorded up to 90% depending upon weed flora and density when weed species reaches above the critical population thresholds (Bhusal and Sanodiya, 2025). Consequently, effective weed management is crucial to realizing the full yield potential of maize. Topramezone [3-(4, 5-Dihydro-3-isoxazolyl)- 2-methyl-4-(methylsulfonyl) phenyl] (5-hydroxy-1- methyl-1H- yrazol-4-yl) methanone] inhibits the hydroxylphenyl pyruvate dioxygenase enzyme of carotenoid biosynthesis (pigment) (Bhusal *et al.*, 2025). The scarcity of agricultural labor has further complicated weed control during critical crop growth stages, making herbicide application the most practical and widely adopted approach for weed management in maize. Herbicides are applied at different growth stages, including pre-plant, pre-emergence, and post-emergence, depending on field conditions and weed spectrum (Chauhan *et al.*, 2017). The use of herbicide mixtures and sequential applications has proven effective in achieving season-long weed control. Atrazine, in particular, is widely used by farmers due to its flexibility in application (pre- and post-emergence), broad-spectrum control, lower cost, and compatibility with other herbicides. However, the excessive and repeated use of atrazine has led to herbicide resistance and weed flora shifts, with 45 weed species worldwide exhibiting resistance to photosystem II (PSII) inhibitors like atrazine. This necessitates the adoption of alternative herbicide modes of action combined with mechanical weed control practices to mitigate the risk of resistance and ensure sustainable maize production. The objective of this study is to assess the efficacy of VLCFA (very-long-chain fatty acid inhibitors) (pyroxasulfone), ALS (acetolactate synthase inhibitors) (halosulfuron-methyl and mesotrione), and 4-HPPD (4-hydroxyphenylpyruvate dioxygenase inhibitors) (tembotrione) herbicides, along with integrated weed management strategies, in suppressing weeds, enhancing yield, and improving the economic viability of maize cultivation under the agro-climatic conditions of Varanasi, Uttar Pradesh. This research aims to develop a sustainable and efficient weed management approach that not only ensures higher crop productivity and profitability for farmers but also mitigates the risks of herbicide resistance and environmental degradation.

Materials and methods

A field study was conducted in *kharif* season of 2023–24 in the All India Coordinated Research Project on maize at Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, India. The experimental site had sandy clay loam soil, neutral pH (6.9), low organic carbon (0.36%), low available nitrogen (178.24 kg/ha), medium phosphorus (22.64 kg/ha), medium potassium (204.35 kg/ha), and normal electrical conductivity (0.17 dS/m). The experiment was laid out in a randomized block design (RBD) with three replications, evaluating twelve weed management treatments: T1-a weedy check (no intervention); T2-a weed-free check; T3-atrazine at 500 g/ha plus hand weeding at 25–30 DAS; T4-pyroxasulfone at 127 g/ha plus hand weeding at 25–30 DAS; T5-atrazine (500 g/ha) followed by halosulfuron methyl at 67 g/ha; T6-atrazine (500/ g/ha) followed by tembotrione at 120 g/ha; T7-atrazine (500 g/ha) followed by topramezone at 25 g/ha; T8-atrazine (500 g/ha) with a mesotrione + atrazine mix at 300 g/ha; T9-pyroxasulfone (127 g/ha) followed by halosulfuron methyl (67 g/ha); T10-pyroxasulfone (127 g/ha) followed by tembotrione (120 g/ha); T11- pyroxasulfone (127 g/ha) followed by topramezone (25 g/ha); and T12- pyroxasulfone (127 g/ha) followed by mesotrione+atrazine (300 g/ha). All post emergence herbicides applications were made at 25–30 DAS. Following pre-irrigation and double plowing in a criss-cross pattern after the mustard harvest, the field was tilled, and maize was sown manually at 25 kg/ha with rows 60 cm apart and plants 20 cm apart. Fertilizers were applied at 150 kg N/ha, 70 kg P_2O_5/ha, and 60 kg K_2O/ha with half the nitrogen applied at sowing and the remainder split at 30 and 55 DAS. Five irrigations were scheduled at critical growth stages (2-leaf, knee-height, tasseling, silking, and grain-filling). Herbicides were applied using a knapsack sprayer calibrated at 500 L/ha. Grain and stover yields (adjusted to 14% moisture) were expressed in quintals per hectare. Plant growth attributes were measured from randomly selected plants, and weed density and dry weight were assessed at 50 DAS using 1 m^2 quadrats. An economic analysis was performed based on input and operational costs, and data were analyzed by ANOVA with treatment differences evaluated using CD and DMRT (Gomez and Gomez, 1984) in SPSS.

Results and discussions

Weed parameters

The application of different herbicidal treatments significantly influenced weed density and dry weight of grasses, sedges, and broad-leaved weeds (BLW) at 50 DAS (Table 1). Among the herbicidal treatments, T4 (pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS) was the most effective, achieving a 70–80% reduction in weed density and dry weight while recording the highest weed control efficiency (96%) and the lowest weed index (4%) at 50 DAS. T12 (pyroxasulfone 127 g/ha *fb* mesotrione + atrazine 300 g/ha) and T3 (atrazine 500 g/ha *fb* hand weeding at 25–30 DAS) were statistically at par with T4 in reducing weed infestation. Among the atrazine-based treatments, T3 significantly reduced weed density and dry weight compared to T5 (atrazine 500 g/ha *fb* halosulfuron methyl 67 g/ha), T6 (atrazine 500 g/ha *fb* tembotrione 120 g/ha) and T7 (atrazine 500 g/ha *fb* topramezone 25 g/ha). However, T5, T6, and T7 were statistically at par with each other but exhibited higher weed biomass accumulation compared to pyroxasulfone-based treatments, highlighting atrazine's limited efficacy against grassy weeds. The superior weed suppression in pyroxasulfone-based treatments is attributed to its long residual activity and inhibition of very-long-chain fatty acid (VLCFA) biosynthesis, preventing weed emergence and regrowth (Mahoney *et al*., 2014). The inclusion of hand weeding in T4 further enhanced its weed control potential. In contrast, atrazine-based treatments, though effective against broadleaf weeds, had limited efficacy on grasses and raised concerns about herbicide resistance (Heap, 2014; Shaner and Beckie, 2014). Overall, T4 (pyroxasulfone 127 g/ha *fb* hand weeding) emerged as the most effective treatment, followed by T12 and T3, ensuring season-long weed suppression and better maize yield potential (Chauhan *et al.*, 2017).

Crop growth parameters

Weed management treatments significantly influenced maize growth parameters, yield, and economic returns (Table 2). At 50 DAS, the weed-free treatment recorded the highest number of leaves per plant, leaf area index (LAI), chlorophyll content (SPAD) and yield parameters whereas the weedy check exhibited the lowest values, highlighting the impact of weed competition on crop growth. Among herbicidal treatments, (pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS outperformed atrazine 500 g/ha *fb* hand weeding at 25-30 DAS in terms of number of leaves per plant (11.3), LAI (0.42) and chlorophyll content (39.6). T12 (pyroxasulfone 127 g/ha fb mesotrione + atrazine 300 g/ha) and T3 (atrazine 500 g/ha fb hand weeding at 25–30 DAS) were statistically at par with T4. Among the atrazine-based treatments, T3 significantly the higher number of leaves per plant, leaf area index (LAI), chlorophyll content (SPAD) and yield parameterst compared to T5 (atrazine 500 g/ha fb halosulfuron methyl 67 g/ha), T6 (atrazine 500 g/ha fb tembotrione 120 g/ha) and T7 (atrazine 500 g/ha fb topramezone 25 g/ha). Similar finding were noted by Bhusal *et al*. (2025).

Yields

Maize yield was notably influenced by weed control practices, with T4 (pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS) recording higher seed index (29.4), grain yield (5.61 t/ha), stover yield (8.14 t/ha), and harvest index (40.8) than T3 (atrazine 500 g/ha *fb* hand weeding at 25-30 DAS) and both T3 and T4 are statistically similar to each other (Table 2). This improvement in yields can be attributed to better reproductive parameters, including higher numbers of cobs per plant, more grain rows per cob, increased grains per row, and greater seed index. These findings align with the research of Ramos *et al.* (2017), who demonstrated that effective weed control significantly improves maize productivity.

Economics

Economic analysis revealed that pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS achieved the higher net returns (120741.8 Rs./ha) and benefit-cost (B:C) ratio of 3.24 in contrast with atrazine 500 g/ha *fb* hand weeding at 25-30 DAS (118291 Rs./ha and 3.0) (Table 2). This was attributed to higher economic yield, and lower cost of cultivation, making it the most economically viable herbicidal treatment. The findings emphasize the need to balance weed control efficiency, yield improvement, and cost-effectiveness for sustainable maize production (Kashe *et al*., 2020).

Table 1. Effect of different herbicidal treatments on weed density, dry weight of grasses, sedges and broad leaved weeds, weed control efficiency and weed index at 50 DAS in maize

Treatments	Weed density (No. /m^2)			Weed dry weight (g/m^2)			Weed control efficiency (%)	Weed index (%)
	Grasses	Sedges	BLW	Grasses	Sedges	BLW		
Weedy-check	11.39(129.3)	10.87(117.7)	10.21(103.67)	4.83(22.85)	6.79(45.60)	4.55(20.22)	0	48
Weedy-free check	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.00)	100	0
Atrazine 500 g/ha + hand weeding at 25-30 DAS	4.14(16.7)	2.96(8.3)	2.68(6.67)	1.10(0.72)	2.10(3.90)	1.30(1.20)	94	6
Pyroxasulfone 127 g/ha + hand weeding at 25-30 DAS	3.32(10.7)	2.40(5.3)	2.19(4.33)	1.03(0.56)	1.94(3.26)	1.01(0.52)	96	4
Atrazine 500g/ha *fb* halosulfuron methyl 67 g/ha at 25-30 DAS	7.15(50.7)	5.91(34.7)	6.59(43)	1.42(1.51)	3.04(8.73)	2.45(5.53)	82	20
Atrazine 500 g/ha *fb* tembotrione 120 g/ha at 25-30 DAS	6.79(45.7)	6.36(40.0)	6.17(37.67)	1.34(1.31)	2.84(7.57)	2.29(4.74)	85	18
Atrazine 500 ga /ha *fb* topramezone 25 g/ha at 25-30 DAS	6.54(42.3)	5.90(34.3)	5.79(33.0)	1.28(1.13)	2.77(7.17)	2.20(4.35)	86	16
Atrazine 500 g/ha *fb* mesotrione + atrazine 300 g/ha at 25-30 DAS	4.90(23.7)	4.21(17.3)	3.67(13.0)	1.18(0.88)	2.50(5.73)	1.50(1.77)	92	10
Pyroxasulfone 127 g/ha *fb* halosulfuron methyl 67 g/ha at 25-30 DAS	6.17(37.7)	4.77(22.3)	5.02(24.67)	1.24(1.03)	2.63(6.40)	2.08(3.84)	87	14
Pyroxasulfone 127 g/ha *fb* tembotrione 120 g/ha at 25-30 DAS	5.70(32.0)	5.37(28.3)	4.56(20.33)	1.21(0.97)	2.60(6.27)	1.79(2.71)	90	13
Pyroxasulfone 127 g/ha *fb* topramezone 25 g/ha at 25-30 DAS	5.32(28.0)	5.05(25.3)	4.10(16.33)	1.18(0.89)	2.43(5.40)	1.58(1.99)	91	11
Pyroxasulfone 127 g/ha *fb* mesotrione + atrazine 300 g/ha at 25-30 DAS	4.63(21.0)	3.34(10.7)	2.97(8.33)	1.10(0.70)	2.20(4.33)	1.36(1.34)	94	8
CD (P=0.05)	0.54	0.51	0.32	0.11	0.15	0.18	-	-
SEm$\pm$	0.18	0.17	0.11	0.04	0.05	0.06	-	-
C.V.	5.72	6.20	4.18	3.90	3.17	5.47	-	-

The values of parenthesis were the original values that had been changed to $\sqrt{(X+0.5)}$; PE – Pre-emergence; DAS – Days after sowing; BLW- Broad leaved weed

Table 2. Effect of different herbicidal treatments on plant growth parameters, yields and economics in maize

Treatments	No. of leaves/ plant	Leaf area index	Chlorophyll content (SPAD value)	Seed index (g)	Grain yield (t/ha)	Stover yield (t/ha)	Harvest index (%)	Net returns (Rs./ha)	B:C
Weedy-check	8.7	0.15	24.2	18.5	3.7	5.3	36.4	53893	1.5
Weedy-free check	11.6	0.43	41.3	35.4	5.9	8.2	41.7	111522	2.1
Atrazine 500g/ha + hand weeding at 25-30 DAS	10.5	0.41	38.3	29.0	5.5	8.2	40.5	118291	3.0
Pyroxasulfone 127 g/ha + hand weeding at 25-30 DAS	11.3	0.42	39.6	29.4	5.6	8.1	40.8	120741	3.2
Atrazine 500g/ha *fb* halosulfuron methyl 67 g/ha at 25-30 DAS	8.0	0.18	24.7	21.2	4.7	7.9	37.2	97225	2.4
Atrazine 500 g/ha *fb* tembotrione 120 g/ha at 25-30 DAS	8.2	0.23	27.0	25.0	4.8	6.5	37.2	102052	2.6
Atrazine 500 g/ha *fb* topramezone 25 g/ha at 25-30 DAS	8.6	0.22	28.6	25.2	4.9	8.3	37.3	106723	2.8
Atrazine 500 g/ha *fb* mesotrione + atrazine 300 g/ha at 25-30 DAS	9.4	0.38	35.7	26.5	5.3	8.1	39.5	112929	2.9
Pyroxasulfone 127 g/ha *fb* halosulfuron Methyl 67 g/ha at 25-30 DAS	9.0	0.33	29.7	25.4	5.0	8.3	37.7	104809	2.5
Pyroxasulfone 127 g/ha *fb* tembotrione 120 g/ha at 25-30 DAS	9.3	0.35	32.3	26.4	5.2	8.3	38.2	108279	2.7
Pyroxasulfone 127 g/ha *fb* topramezone 25 g/ha at 25-30 DAS	9.6	0.37	33.7	21.6	5.2	8.3	38.6	111724	2.9
Pyroxasulfone 127 g/ha *fb* mesotrione + atrazine 300 g/ha at 25-30 DAS	10.0	0.40	37.1	26.7	5.4	8.1	40.0	113878	2.7
CD (P=0.05)	2.32	0.10	2.501	7.28	1.36	1.45	2.40	-	-
SEm±	0.79	0.04	0.847	2.48	0.45	0.45	0.82	-	-
C.V.	14.42	18.77	4.487	16.63	1.58	10.96	3.65	-	-

Conclusion

Given the limitations of atrazine-based treatments, adopting herbicides with diversified modes of action and integrated weed management strategies is essential for effective weed suppression, yield maximization, and economic sustainability in maize cultivation. Thus, for effective weed control, and higher yields and economic returns, application of pyroxasulfone 127 g/ha *fb* hand weeding at 25–30 DAS can be suggested under the agro-climatic conditions of Varanasi, Uttar Pradesh.

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