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Effects of sequential and combined application of tank-mix herbicides on weed growth and productivity of maize (*Zea mays*)

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In India, maize (*Zea mays* L.) is mainly grown in the rainy (*kharif)* season which is affected by heavy rain and increased relative humidity, and owing to wider spacing weeds find more space to grow and compete for nutrients, sunlight and water besides hindering efficient weed management practices. Maize plays a crucial role in the rice-wheat cropping system in India by diversifying crop rotations, improving soil health (continuous incorporation of residues in soil) and enhancing overall farm productivity. Recently, more than 47% of maize produced in India is used for poultry feed while 14% is utilized for starch production. Approximately 13% is designated for both food consumption and livestock feed, 7% for food processing and the remaining 6% is exported or allocated for other purposes (IIMR 2021). Compared to two hand weeding (20 and 40 DAS), a reduction in the maize grain yield by 58.7% is observed under the weedy condition (Triveni *et al*. 2017). Manual weeding controls weeds effectively but due to its higher cost and labour-intensive nature it becomes uneconomical under erratic rainfall and in wet soil condition. Under these circumstances, weeds can be effectively controlled by chemical application. It is necessary to apply pre-emergence and post-emergence herbicides both sequentially and simultaneously in order to keep weeds under control at initial stages of crop. Atrazine is commonly used in maize crops and can be applied as both pre-and post-emergence. It effectively controls a broad range of weeds. But the use of atrazine in maize has limitations, viz. residual effects on subsequent crops or non-target plants while weeds develop resistance against herbicide. The highest value of weed control efficiency (WCE) was reported in maize when atrazine at -1.0 kg a.i./ha as pre-emergence was followed by (*fb*) one manual weeding at 30 DAS (Sunitha *et al.* 2010). In recent times, two novel post-emergent herbicides have been introduced; tembotrione and topramezone. Topramezone being highly selective herbicide controls both broadleaf and grassy weeds within 2–5 DAS in maize while atrazine can be applied immediately after sowing as a pre-emergence treatment as well as post-emergence herbicide at 30 DAS (Swetha *et al.* 2018). Atrazine, which can be mixed with tembotrione and topramezone, may be used as an early post-emergence, i.e. up to 10–15 DAS to control a wide range of weed species in maize (Akhtar *et al.* 2017). Hence, there is a need to explore the use of new post-emergence herbicides like tembotrione and topramezone in an optimum combination with atrazine that can provide efficient and broader weed control in maize.

The present study was carried out at Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand during the rainy (*kharif)* season of 2021–22. Soil of the experimental field was silty clay loam in texture, has a neutral *p*H value of 7.7, a high organic carbon content of 0.88%, low available nitrogen value of 253.1 kg/ha, medium available phosphorus value of 16.6 kg/ha and potassium value of 164.0 kg/ha. The study comprised of nine treatments, viz. T_1, Weedy; T_2, Weed free; T_3, Atrazine - 1 kg a.i./ha PE *fb* hand weeding at 21 DAS; T_4, Atrazine - 0.75 kg a.i./ha PE *fb* Topramezone - 25.2 g a.i./ha; T_5, Atrazine - 0.75 kg a.i./ha PE *fb* Tembotrione - 120 g a.i./ha; T_6, Atrazine - 1.0 kg a.i./ha PE *fb* Topramezone - 25.2 g a.i./ha; T_7, Atrazine - 1.0 kg a.i./ha PE *fb* Tembotrione - 120 g a.i./ha; T_8, Topramezone - 25.2 g a.i./ha + Atrazine - 0.75 kg a.i./ha; T_9, Tembotrione - 120 g a.i./ha + Atrazine - 0.75 kg a.i./ha. The experiment was conducted in RBD and replicated thrice. The hybrid variety DKC 9144 was grown with a spacing of 60 cm × 25 cm on June 24, 2021, and harvested on October 12, 2021. The field was prepared by one ploughing and cross harrowing thrice with a tractor-drawn disc harrow. Tractor-drawn levelers were used to level the field. Nutrient levels were applied at 120 kg of nitrogen, 60 kg of phosphorus and 40 kg of potassium and 25 kg of

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zinc sulfate for each hectare. One-third of nitrogen dose, entire phosphorus (in furrows), potassium and zinc sulfate (in the side of furrows) were applied at sowing. The rest of the nitrogen was sprayed at knee height and at tasseling in two equal doses.

Atrazine was applied as pre-emergence just after sowing whereas post-emergence herbicides, i.e. tembotrione and topramezone were applied at 30 DAS. Single tank-mix application of herbicides was made as an early post-emergence treatment at 15 DAS. Under weed-free treatment, manual weeding was performed to control weeds thrice at 18, 30 and 42 DAS. A flat fan nozzle was used to apply the herbicides at a spray volume of 500 litres/ha. Observations on weed flora were taken at 50 DAS. Weed samples were collected using a quadrat size of 1.0 m^2 then shade dried for 2–3 days after that dried in a hot air oven at 65±5°C till the constant weight was achieved. A digital balance was used to determine the dry weight of weeds and was expressed in g/m^2. The data on weeds, viz. weed density and their dry weight were normalized by square root transformation with an additional factor of 1.0. The information regarding the total weed density data is mentioned in Table 1.

The weedy plot had the highest total weed density ($369.3/m^2$) at 50 DAS which was significantly higher than other treatments. Tank mix application of topramezone + atrazine resulted in significantly lower total weed density and was similar to other herbicidal treatments. This was due to the efficient control of early-emerging weeds by the early post-emergence tank mix application (Lavanya *et al.* 2021). At 50 DAS, weedy treatment had significantly higher total weed dry matter accumulation (441.5 g/m^2). At 50 DAS, all herbicidal treatments were statistically similar in respect of total dry matter accumulated with the maximum value (116.9 g/m^2) in sequential application of atrazine -1.0 kg a.i./ha and topramezone -25.2 g/ha. The herbicidal treatments prevented further germination of susceptible weed species resulting in a lower weed population and total dry matter accumulation (Samant *et al.* 2015).

The weed control efficiency (WCE) varied among treatments depending on the method used for weed control. At 50 DAS, both sequential and tank mix treatments had similar WCE with the highest value (79.9%) observed in tank mix application of topramezone -25.2 g a.i./ha + atrazine -0.75 kg a.i./ha (Table 1). The WCE was higher at 50 DAS due to the increased dry weight of weeds in the weedy treatment whereas in herbicidal treatments, it decreased. The lowest weed index (3.5%) was observed in treatment including atrazine (-1 kg a.i./ha) *fb* hand weeding. Sequential application treatments, i.e. atrazine (-0.75 kg a.i./ha) *fb* topramezone, atrazine (-0.75 kg a.i./ha) *fb* tembotrione and atrazine (-1.0 kg a.i./ha) *fb* topramezone showed a slightly higher weed index (7.9, 7.6 and 7.8%, respectively) compared to tank mix application treatments i.e. topramezone + atrazine and tembotrione + atrazine (10.6 and 9.5%, respectively). The weedy crop showed a weed index of 51.6%, indicating that the weeds reduced

Table 1 Effect of pre-and post-emergence herbicides on weed growth and yield of *kharif* maize

Treatment	Total weed density (no./m^2)	Total weed dry matter (g/m^2)	Weed control efficiency (%)	Weed index (%)	Grain yield (t/ha)	Stover yield (t/ha)	Cost of cultivation (₹/ha)	Net returns (× 1000 ₹/ha)	Net B:C
T_1	19.1 (369.3)	20.9 (441.5)	0.0	51.6	3.46	5.98	32,588	32.09	0.98
T_2	1.0 (0.0)	1.0 (0.0)	100.0	0.0	7.20	9.81	48,338	86.34	1.79
T_3	15.6 (244.0)	10.2 (104.1)	75.6	3.5	6.94	9.38	39,338	90.52	2.30
T_4	14.0 (197.3)	9.7 (93.9)	78.1	7.9	6.60	9.01	38,888	84.60	2.18
T_5	14.3 (205.3)	10.1 (105.6)	74.2	7.6	6.65	9.50	38,888	85.58	2.20
T_6	16.2 (262.7)	10.6 (116.9)	71.5	7.8	6.67	9.13	39,088	85.56	2.19
T_7	15.4 (237.3)	9.6 (93.7)	78.9	4.7	6.88	9.25	39,088	89.58	2.29
T_8	13.9 (197.3)	9.2 (84.7)	79.9	10.6	6.42	8.95	38,188	81.81	2.14
T_9	14.6 (214.7)	10.0 (102.3)	76.1	9.5	6.50	8.88	38,188	83.50	2.19
SEm ±	0.8	0.9	-	-	0.41	0.37	-	7.81	0.20
LSD (P=0.05)	2.5	2.7	-	-	1.26	1.14	-	23.62	0.62

Data given in parenthesis are original value. Refer to the methodology for treatment details.

maize grain yield by nearly 50% in comparison to weed free crop.

The grain yield (7.2 t/ha) was highest under weed-free treatment that was similar to all herbicide-treated crops and significantly higher than the weedy crop. Among herbicide treatments, sequential and tank mix applications showed similar results for grain yield. The weedy crop had the lowest grain yield (3.4 t/ha) which was 51.9% lower than the weed-free crop. Sequential application of herbicides, i.e. atrazine (-0.75 kg a.i./ha) *fb* topramezone, atrazine (-0.75 kg a.i./ha) *fb* tembotrione, atrazine (-1.0 kg a.i./ha) *fb* topramezone and atrazine (-1.0 kg a.i./ha) *fb* tembotrione resulted in higher grain yield (90.9%, 92.4%, 92.7%, and 98.8%, respectively) compared to the weedy treatment. Similarly, the yield increased in tank mix applications of topramezone + atrazine and tembotrione + atrazine by 85.5% and 88.1%, respectively compared to the weedy treatment. The reduced weed competition favoured the optimum conditions for crop growth and ultimately contributed to the higher grain yield. There was a non-significant difference between tembotrione and topramezone in maize grain yield for sequential and tank mix atrazine applications (Sundari *et al.* 2019). The stover yield under weedy treatment was significantly lower (5.98 t/ha) indicating a significant decrease of 38.9% in comparison to weed free treatment. The highest stover yield (9.38 t/ha) among the herbicidal treatments was attained by atrazine (-1 kg a.i./ha) *fb* hand weeding. Atrazine (-1 kg a.i./ha) *fb* hand weeding treatment resulted in the highest net return (₹90,527/ha) which was similar to all treatments except for the weedy treatment. The significantly lowest net return was recorded from the weedy crop. Weed-free treatment was at par with both sequential as well as tank mix treatments.

Owing to three times manual weeding under weed-free treatment resulted in the highest cultivation cost (₹48338/ha) which was statistically at par with atrazine (-1 kg a.i./ha) *fb* hand weeding due to the combined cost incurred in herbicide application and one time manual weeding. Among sequential application treatment, atrazine (-0.75 kg a.i./ha) *fb* topramezone and atrazine (-0.75 kg a.i./ha) *fb* tembotrione showed lower cultivation costs due to 25% less atrazine used in these treatments while under tank mix application, i.e. topramezone + atrazine and tembotrione + atrazine showed the lowest cultivation cost. This was achieved possibly by applying two herbicides at once and lowering the dosage of atrazine by 25%.

Atrazine (-1 kg a.i./ha) *fb* hand weeding attained the highest net B:C (benefit-to-cost) ratio of 2.3 which was statistically similar to all herbicidal treatments and the weed-free treatment but significantly superior to the weedy treatment (Mitra *et al*. 2018). The weedy treatment had a significantly lower net B:C ratio of 0.98. The net return and the cost of cultivation were used for calculation of net B:C ratio. Variations in net return and cost of cultivation contributed to the differences in the reported net B:C ratio amongst the treatments (Kakade *et al.* 2020).

SUMMARY

The field experiment was conducted at G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand during *kharif* season 2021–22 to evaluate the effects of tank-mix herbicides on weeds and maize (*Zea mays* L.) in order to determine the optimum dosage, application time and combinations of herbicides for maize. Based on the findings, it could be concluded that weed-free conditions are just as effective as atrazine applied with tembotrione or topramezone through sequential or tank mix application for reducing weeds effectively and increasing grain yield. Tank mix treatments of topramezone (25.2 g a.i./ha) and tembotrione (120 g a.i./ha) with reduced dose of atrazine (0.75 kg a.i./ha) should be employed by farmers since it not only removes weeds effectively but, also offers a better environment for maize to grow providing high profits for farmers. It also lowers the dose and expenses involved in manual weeding and spraying atrazine separately.

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