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EVALUATION OF HERBICIDE EFFICACY ON WEED DYNAMICS AND YIELD OF MAIZE IN MAIZE-SUNFLOWER CROPPING SYSTEM

Y. Lavanya[1]*, K. Srinivasan[1] and P Murali Arthanari[1]

[1]*Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore-641 003, Tamil Nadu, India*

ABSTRACT

A field experiment was conducted for two consecutive years during the *kharif* seasons of 2018 and 2019 at Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu. The field trial comprised ten treatments: pre-emergence (PE) application of atrazine followed by hand weeding, atrazine as PE followed by power weeding, PE atrazine + pendimethalin as a tank mix, PE atrazine + pendimethalin as a tank mix followed by hand weeding, topramezone as early post-emergence (EPOE), PE atrazine followed by EPOE topramezone, EPOE tembotrione, PE atrazine followed by EPOE tembotrione, control, and two hand weedings (weed-free). The PE atrazine followed by topramezone as EPOE significantly reduced the weed index (1.9) and increased weed control efficiency (85.7% and 75.9% at 60 and 90 DAS, respectively). This treatment also resulted in a higher maize grain yield of 8237 kg ha^{-1}, which was statistically comparable to the weed-free plot (8398 kg ha^{-1}) compared to other treatments. Consequently, it can be inferred that atrazine as a pre-emergence herbicide, followed by topramezone as an early post-emergence herbicide application, proved to be a highly effective approach for controlling weeds in maize crop.

Keywords: Atrazine, Pendimethalin, Tembotrione, Topramezone, Weed indices

Maize (*Zea mays*) occupies a significant position among cereal crops worldwide, serving as a staple food for millions of people and providing essential feed for livestock. Its production plays a pivotal role in ensuring food security and driving economic growth in numerous countries (FAOSTAT, 2021). However, weeds present a significant challenge to crop productivity, as they compete with maize for essential resources such as nutrients, water, and sunlight, ultimately leading to reduced yields (Zimdahl, 2018).

Weed management is a critical aspect of maize production, and various strategies have been employed to control weeds and mitigate their negative impacts on crop performance. Among these strategies, the use of herbicides has emerged as a popular and effective approach for weed control in maize (Heap, 2021). Herbicides are chemical substances specifically designed to target and kill unwanted plants, offering an efficient means of weed control.

The objective is to evaluate the effectiveness of herbicides in controlling weeds in maize crop, focusing primarily on investigating the impact of herbicides on weed density, assessing their effect on weed biomass, evaluating their influence on maize yield, and calculating weed management indices. These indices provide a comprehensive evaluation of herbicide efficacy by integrating multiple parameters such as weed density, biomass, and crop yield (Samanth *et al.*, 2015). They allow for a standardized and objective assessment of herbicide effectiveness in weed management and optimizing maize crop performance. Furthermore, weed control indices facilitate the development of integrated weed management (IWM) strategies by incorporating multiple factors into a single metric (Liebman and Gallandt, 1997).

IWM promotes sustainable weed management practices and reduces over-reliance on herbicides, thus minimizing the risk of herbicide resistance and environmental impacts. Weeds not only reduce crop yields but also escalate production costs, harbor insects and diseases, lower the quality of produce, and diminish land value, collectively contributing to a decrease in crop production (Subramanian *et al.*, 1993). Therefore, effective weed management is crucial for improving maize productivity.

MATERIAL AND METHODS

The experiment was conducted at TNAU in Coimbatore during the *kharif* seasons of 2018 and 2019. The experimental site featured sandy clay loam soil with specific characteristics: a pH of 8.36 (saline), low nitrogen availability (218 kg ha^{-1}), medium phosphorus availability (11.7 kg ha^{-1}), high potassium availability (424 kg ha^{-1}), and a low organic carbon content of 0.36%. It followed a randomized complete block design, consisting of ten treatments and three replications.

*Corresponding author: yenabalalavanya@gmail.com
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Details of treatments:

S. No.	Treatments	Time of application (DAS)	Dosage (a.i. ha^{-1})
T_1	Atrazine 50 % WP as PE *fb* HW	1 *fb* 20	0.5 kg
T_2	Atrazine 50 % WP as PE *fb* PW	1 *fb* 20	0.5 kg
T_3	Atrazine 50 % WP + Pendimethalin 30 % EC (Tank mix) as PE	1	0.5 kg + 1 kg
T_4	Atrazine 50 % WP + Pendimethalin 30 % EC (Tank mix) as PE *fb* HW	1 *fb* 20	0.5 kg + 1 kg
T_5	Topramezone 33.6% SC as EPOE	20	25.2 g
T_6	Atrazine as 50 % WP PE *fb* Topramezone 33.6% SC as EPOE 66-	1 *fb* 20	0.5 kg *fb* 25.2 g
T_7	Tembotrione 42% SC as EPOE	20	122 g
T_8	Atrazine 50 % WP as PE *fb* Tembotrione 42% SC as EPOE	1 *fb* 20	0.5 kg *fb* 122 g
T_9	Weed free	20 and 45	-
T_{10}	Control	-	-

Note: DAS=Days after sowing, EC=emulsifiable concentrate, *fb*=followed by, HW=hand weeding, PE=pre emergence, EPOE=early post emergence, PW=power weeding, SC= soluble concentrate and WP=wettable powder

The total plot size was 4.8 m x 4.5 m, with each net plot measuring 2.4 m x 3.5 m. The test cultivar used was 'TNAU maize hybrid Co 6', with a duration of 110 days. Seeds were manually dibbled with a spacing of 60 cm × 20 cm, at a seed rate of 20 kg ha^{-1}. Following sowing, a light irrigation of 50 mm was immediately provided. Recommended fertilizer application consisted of N:P:K at a rate of 250:75:75 kg ha^{-1}, with the entire quantity of phosphorus (P) and potassium (K) applied as basal application, while the nitrogen (N) fertilizer was split into three applications: basal (50%), 25 days after sowing (DAS) (25%), and 45 DAS (25%).

At 30 and 60 days after sowing (DAS), data regarding associated weeds were collected. Weed count was conducted randomly from four locations within each plot using a 50 cm x 50 cm quadrant (0.25 m^2). Weeds found within the quadrant were carefully uprooted, and the root section was thoroughly cleaned to detach any attached soil. Subsequently, the weeds were dried in an oven at 60°C for 36 to 48 hours. Once completely dried, the biomass of the weeds was recorded. Similarly, in each plot, five maize plants were randomly selected, and their biomass was measured. The weed biomass values were then computed and adjusted to per square meter values at 60 and 90 DAS. The density and biomass of weed data were calculated to per square meter values and underwent square root transformation for statistical analysis. Yields from different plots were recorded at harvest. Various weed indices, including Weed Control Efficiency (WCE), Weed Control Index (WCI), Weed Management Index (WMI), Weed Persistence Index (WPI), Crop Resistance Index (CRI), Treatment Efficiency Index (TEI), and Weed Index (WI) (Sarma, 2015), were calculated using the following equations.

$$\text{WCE} = \frac{\text{(Weed density in control plot – weed density in treated plot)}}{\text{(weed density in control)}} \times 100$$

$$\text{WCI} = \frac{\text{(Weed drymatter in control plot – weed drymatter in treated plot)}}{\text{(weed drymatter in control)}} \times 100$$

$$\text{WI} = \frac{\text{(yield from weed free plot – yield from treated plot)}}{\text{(yield from weed free plot)}} \times 100$$

$$\text{WPI} = \frac{\text{weed biomass in treated plot}}{\text{weed biomass in control plot}} \times \frac{\text{weed density in control plot}}{\text{weed density in treated plot}}$$

$$\text{CRI} = \frac{\text{crop biomass in treated plot}}{\text{crop biomass in control plot}} \times \frac{\text{weed biomass in control plot}}{\text{weed biomass in treated plot}}$$

$$\text{TEI} = \frac{\text{(yield from treated plot – yield from control plot)/yield from control plot}}{\text{(Weed biomass in control plot – weed biomass in treated plot)}}$$

$$\text{WMI} = \frac{\text{(yield from treated plot – yield from control plot)/yield from control plot}}{\text{(Weed biomass in control plot – weed biomass in treated plot)/(Weed biomass in control)}}$$

The transformed data underwent analysis using Fisher's Analysis of Variance (ANOVA) as per Panse and Sukhatme (1967). In instances where the F-test yielded statistical significance, treatment means were compared using an appropriate least significant difference (LSD) threshold. The analysis was conducted at a significance level of 5%, with subsequent presentation and discussion of the findings.

RESULTS AND DISCUSSION

Effect on weeds

The weed composition in the experimental trial was predominantly characterized by broad-leaved species, notably *Trianthema portulacastrum*, alongside grasses such as *Dactyloctenium aegyptium* throughout both years of the study. Furthermore, in the second year, sedges, particularly *Cyperus rotundus*, were observed.

Lower-density weed species, including *Digera arvensis* and *Amaranthus viridis*, were also present. In the control (weedy) plots, the density of broad-leaved weeds remained consistently high at all crop stages, consistent with findings reported in a study on integrated weed management in hybrid maize by Kamble *et al.* (2005).

The results presented in Table 1 illustrate the significant impact of treatments on weed density at both 60 and 90 days after sowing (DAS). Throughout the growing period, weed density showed an increase from 60 to 90 DAS. Initially, the treatment combining atrazine as pre-emergence (PE) at 0.5 kg ha^{-1} followed by topramezone as early post-emergence (EPOE) at 25.2 g ha^{-1} exhibited the lowest total weed density at 60 DAS. However, by 90 DAS, the efficacy of the herbicide was diminished at the recommended dosage, leading to the emergence and growth of new weed flushes. Fortunately, this herbicide-induced emergence did not adversely affect crop growth, consistent with findings reported by Varshitha *et al.* (2019), attributed to the crop's higher growth rate.

Significantly, the lowest total weed density was observed with the treatment combination of atrazine as PE at 0.5 kg ha^{-1} followed by tembotrione as EPOE at 122 g ha^{-1}, which was comparable to hand weeding (HW) performed at 20 and 45 DAS. Moreover, all weed management treatments had a significant effect on weed dry matter, exhibiting a similar trend to weed density as indicated in Table 1. PE atrazine at 0.5 kg ha^{-1} followed by EPOE topramezone at 25.2 g ha^{-1} recorded the lowest total weed biomass at both 60 and 90 DAS, consistent with the findings obtained from the treatment combination of atrazine as PE at 0.5 kg ha^{-1} followed by topramezone as EPOE at 25.2 g ha^{-1} and HW performed at 20 and 45 DAS.

Atrazine as pre-emergence (PE) at 0.5 kg ha^{-1} followed by tembotrione as early post-emergence (EPOE) at 122 g ha^{-1} demonstrated the highest Weed Control Efficiency (WCE) of 85.7% and Weed Control Index (WCI) of 75.9%, as indicated in Table 1. This was followed by the combination of PE atrazine at 0.5 kg ha^{-1} followed by EPOE tembotrione at 122 g ha^{-1}, which achieved WCE of 86.1% and WCI of 77.6%. These results surpassed those obtained from hand weeding (HW) conducted at 20 and 45 days after sowing (DAS). WCE and WCI values directly reflect the effectiveness

Table 1. Weed density (No./m^2), weed biomass (g/m^2), weed control efficiency (%) and weed control index (%) in maize at 60 and 90 DAS with various weed control methods (pooled data of 2 years)

Treatment		Weed density (No./m^2)		Weed biomass (g/m^2)		WCE (%)		WCI (%)	
		60 DAS	90 DAS	60 DAS	90 DAS	60 DAS	90 DAS	60 DAS	90 DAS
T_1:	Atrazine *fb* HW	4.6 (21.0)	6.1 (36.3)	5.0 (24.6)	6.8 (46.3)	82.8	65.0	82.8	67.5
T_2:	Atrazine *fb* PW	6.5 (41.2)	7.7 (58.7)	6.9 (47.7)	8.6 (74.2)	66.3	43.5	66.6	47.8
T_3:	Atrazine + Pendimethalin (Tank mix)	7.2 (50.7)	8.4 (70.8)	7.8 (59.9)	9.4 (87.1)	58.6	31.8	58.1	38.7
T_4:	Atrazine + Pendimethalin (Tank mix) *fb* HW	4.6 (20.8)	6.0 (35.7)	5.0 (24.0)	6.7 (44.1)	83.0	65.6	83.2	68.4
T_5:	Topramezone	6.1 (36.5)	6.2 (38.0)	6.6 (42.6)	7.0 (48.6)	70.2	63.4	70.2	65.8
T_6:	Atrazine *fb* Topramezone	4.2 (17.5)	5.0 (25.0)	4.5 (19.9)	5.7 (31.8)	85.7	75.9	86.1	77.6
T_7:	Tembotrione	6.2 (37.7)	6.3 (39.0)	6.7 (43.9)	7.1 (49.7)	69.2	62.4	69.3	65.1
T_8:	Atrazine *fb* Tembotrione	4.4 (18.7)	5.2 (26.3)	4.6 (20.4)	5.8 (33.2)	84.7	74.6	85.7	76.7
T_9:	Hand weeding	3.1 (9.0)	4.9 (23.2)	3.3 (10.1)	5.4 (29.1)	92.6	77.7	92.9	79.5
T_{10}:	Control	11.1 (122.3)	10.2 (103.8)	12.0 (142.9)	11.9 (142.2)	0.0	0.0	0.0	0.0
SE(d)		0.2	0.1	0.2	0.1				
CD ($p \leq 0.05$)		0.5	0.4	0.6	0.4				

Note: HW (hand weeding); PW (power weeder); *fb* (followed by)
(Values in parentheses are original values, which were transformed $\sqrt{X + 0.5}$ and statistically analysed)

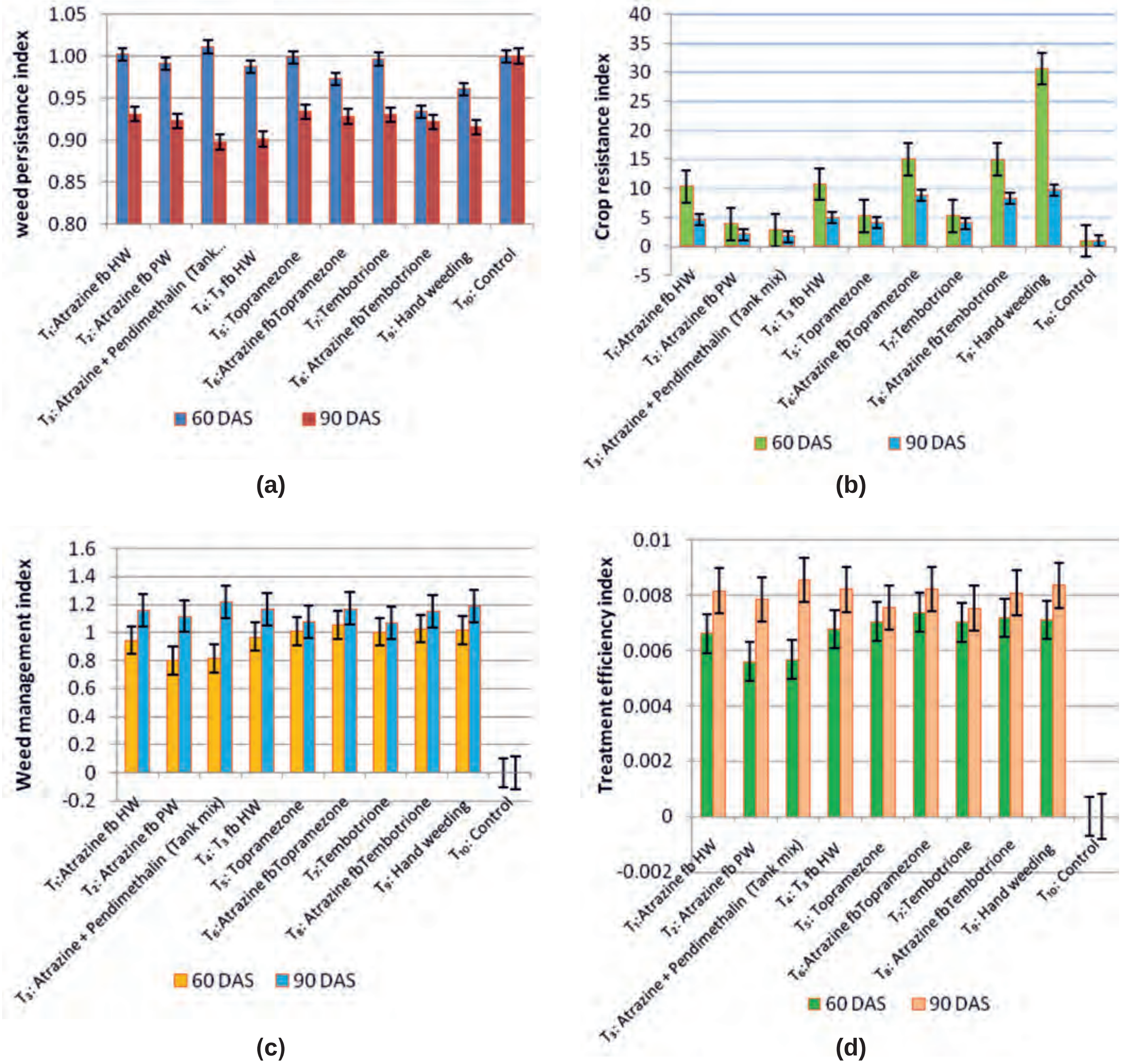

Fig. 1. Weed indices of maize at 60 and 90 DAS in response to weed control methods (pooled data of two years) (a) Effect of herbicides on weed persistence index (WPI) at different intervals (b) Effect of herbicides on crop resistance index (CRI) at different intervals (c) Effect of herbicides on weed management index (WMI) at different intervals (d) Effect of herbicides on treatment efficiency index (TEI) at different intervals

of herbicide treatments in weed control. The sequential application of PE followed by EPOE herbicide facilitated the control of different waves of weed growth, resulting in higher WCE and WCI compared to other treatments. Similar findings were reported by Rajeshkumar *et al.* (2017) and Gaurav *et al.* (2018).

The combination of pre-emergence (PE) atrazine at 0.5 kg ha^{-1} with pendimethalin at 1 kg ha^{-1} (Tank mix) resulted in a higher Weed Persistence Index (WPI) of 1.01 at 60 days after sowing (DAS), whereas the combination of PE atrazine at 0.5 kg ha^{-1} with early post-emergence (EPOE) topramezone at 25.2 g ha^{-1} applied at 20 DAS showed a WPI of 0.94 at 90 DAS (Fig. 1a). These findings suggest the resistance of escaped weeds to the implemented control measures.

The Crop Resistance Index (CRI) was utilized to gauge the enhanced vigor of crop plants resulting from weed control measures (Fig. 1b). Among the evaluated

Table 2. Crop dry matter (at 60 and 90 DAS), grain yield (at harvest) and weed index of maize in response to weed control methods (pooled data of two years)

Treatment		Dry matter of maize (kg ha^{-1})		Grain yield of maize (kg ha^{-1})			Weed index
		60 DAS	90 DAS	2018	2019	Pooled	
T_1:	Atrazine *fb* HW	6402	9454	7597	7796	7697	8.3
T_2:	Atrazine *fb* PW	4692	6863	6673	6572	6623	21.1
T_3:	Atrazine + Pendimethalin (Tank mix)	4196	6732	6384	6324	6354	24.3
T_4:	Atrazine + Pendimethalin (Tank mix) *fb* HW	6552	9570	7738	7856	7797	7.2
T_5:	Topramezone	5761	8729	7243	7501	7372	12.2
T_6:	Atrazine *fb* Topramezone	7608	12187	8198	8276	8237	1.9
T_7:	Tembotrione	5799	8679	7162	7482	7322	12.8
T_8:	Atrazine *fb* Tembotrione	7737	12096	8065	8174	8120	3.3
T_9:	Hand weeding	7844	12291	8374	8421	8398	0.0
T_{10}:	Control	3623	6220	4387	4246	4317	48.6
SE(d)		157	103	146	130	138	
CD (p≤0.05)		351	274	316	283	300	

Note: HW (hand weeding); PW (power weeder); *fb* (followed by)

treatments, the combination of pre-emergence (PE) atrazine at 0.5 kg ha^{-1} with early post-emergence (EPOE) topramezone at 25.2 g ha^{-1} applied at 20 days after sowing (DAS) demonstrated the highest crop resistance indices, with values of 15.11 at 60 DAS and 8.76 at 90 DAS. This was closely followed by the combination of PE atrazine at 0.5 kg ha^{-1} with EPOE tembotrione at 122 g ha^{-1}, which exhibited crop resistance indices of 14.98 at 60 DAS and 8.33 at 90 DAS. These results suggest that these herbicide treatments had a much lesser detrimental effect on the crop compared to the other treatments, as evidenced by their higher CRI values.

The weed-killing potential of different herbicide treatments was assessed using the Treatment Efficiency Index (TEI), as depicted in Fig. 1d. The combination of pre-emergence (PE) atrazine at 0.5 kg ha^{-1} with early post-emergence (EPOE) topramezone at 25.2 g ha^{-1} applied at 20 days after sowing (DAS) exhibited the highest TEI values at both 60 DAS (6.53) and 90 DAS (4.06), followed by the combination of PE atrazine at 0.5 kg ha^{-1} with EPOE tembotrione at 122 g ha^{-1} applied at 20 DAS (6.18 and 3.17 at 60 DAS and 90 DAS, respectively). Additionally, at 60 DAS, the combination of PE atrazine at 0.5 kg ha^{-1} with EPOE topramezone at 25.2 g ha^{-1} displayed the highest Weed Management Index (WMI) of 1.05, while at 90 DAS, the combination of PE atrazine at 0.5 kg ha^{-1} with pendimethalin 30% at 1 kg ha^{-1} (Tank mix) showed a WMI of 1.22 (Fig. 1c).

Effect on crop

The treatments significantly influenced crop biomass at both 60 and 90 days after sowing (DAS), as shown in Table 2. The highest crop growth and maize grain yield were recorded under hand weeding twice at 20 and 45 DAS, followed by pre-emergence (PE) atrazine at 0.5 kg ha^{-1} followed by either early post-emergence (EPOE) topramezone at 25.2 g ha^{-1} or EPOE tembotrione at 122 g ha^{-1}. This combination recorded a 6.5% yield advantage over the recommended herbicide PE atrazine 50% WP at 0.5 kg ha^{-1} followed by hand weeding at 20 DAS, attributed to the wide spectrum of weed control during the critical crop-weed competition period, supporting the findings of Hawaldar and Agasimani (2012). The uncontrolled weeds in the weedy check caused approximately a 47.5% maize grain yield loss compared to PE atrazine at 0.5 kg ha^{-1} followed by EPOE topramezone at 25.2 g ha^{-1} (Table 2).

The lowest Weed Index (WI) (Table 2) was recorded at 1.9 with atrazine as pre-emergence (PE) at 0.5 kg ha^{-1} followed by topramezone as early post-emergence (EPOE), which was comparable to atrazine as PE at 0.5 kg ha^{-1} followed by tembotrione as EPOE at 122 g ha^{-1} at 20 days after sowing (DAS) (3.3). Compared to the sequential application of both EPOE herbicides with atrazine at 0.5 kg ha^{-1}, the sole application of topramezone and tembotrione recorded a higher weed index because it no longer had an effect on the second and third flushes of weeds that emerged after 60 to 90 DAS. Similar findings were observed by Singh *et al.* (2017) and Nazreen *et al.* (2018).

CONCLUSION

In conclusion, the combination of pre-emergence

(PE) atrazine at 0.5 kg ha^{-1} followed by early post-emergence (EPOE) topramezone at 25.2 g ha^{-1} demonstrated superior effectiveness in weed control for maize. This sequential application of herbicides resulted in the lowest levels of weed density, biomass, Weed Persistence Index (WPI), and Weed Index (WI), while achieving the highest levels of Weed Control Index (WCI), Weed Control Efficiency (WCE), Crop Resistance Index (CRI), Treatment Efficiency Index (TEI), and Weed Management Index (WMI). Additionally, it resulted in higher maize yield, comparable to the weed-free treatment.

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Authors' contribution

Conceptualization and designing of the research work (YL, KS and PMA); Execution of field/lab experiments and data collection (YL); Data analysis and interpretation (YL); Preparation of manuscript (YL).

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