Indian Journal of Weed Science **51**(2): 145–150, 2019

Print ISSN 0253-8040 Online ISSN 0974-8164

Mesotrione and atrazine combination to control diverse weed flora in maize

R.S. Chhokar*, R.K. Sharma, S.C. Gill and R.K. Singh

Resource Management Unit, ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana 132001, India

**Email: rs_chhokar@yahoo.co.in*

Article information

DOI: 10.5958/0974-8164.2019.00032.7

Type of article: Research article

Received : 27 March 2019
Revised : 7 June 2019
Accepted : 9 June 2019

Key words

Atrazine, Grass weeds

Maize

Mesotrione

2,4-D-Na

Synergism

Tank-mix

ABSTRACT

Field and pot studies were conducted during two rainy *(Kharif)* seasons of 2013 and 2014 to identify the effectiveness and optimum dose of mesotrione and atrazine combination for diverse weed flora management in maize. The weed control treatments evaluated in field experiment were pre-emergence atrazine 1000 g/ha and post-emergence 2,4-D-Na 1000 g/ha, mesotrione 120 g/ha and ready mixture of mesotrione with atrazine in ratio of 1:10 w/w (Calaris Xtra 275 SC) at 750, 875 and 1000 g/ha. The major weeds infested were *Dactyloctenium aegyptium*, *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Trianthema portulacastrum*, *Digera arvensis* and *Phyllanthus niruri*. The uncontrolled weed competition reduced the maize yield by 38.7 to 54.0%. Mesotrione 120 g/ha was effective in controlling the broad-leaved weeds but was poor in controlling grass weeds. The weed control with pre-emergence atrazine 1000 g/ha was also not consistent. However, in pot and field studies, ready or tank mixture of mesotrione with atrazine was synergistic and superior in controlling weeds than to sole mesotrione and atrazine applications. The weed control efficiencies with ready-mixture of mesotrione + atrazine (1:10 w/w) at 875 and 1000 g/ha ranged 89-99%. Mesotrione plus atrazine at 875 and 1000 g/ha yielded (7.74-8.11 t/ha) significantly higher as compared to mesotrione 120 g/ha (5.83-5.96 t/ha), atrazine 1000 g/ha (5.93-6.70 t/ha) and 2.4-D-Na 1000 g/ha (3.82-5.30 t/ha) applications, as well as, untreated weedy check (3.73-4.76 t/ha). The results showed that mesotrione and atrazine combination has synergistic effect, which can be used for managing diverse weed flora in maize.

INTRODUCTION

Weed infestation in maize is the key detrimental factor causing huge grain yield losses because of wide row spacing and slow initial crop growth along with frequent rains during rainy season. Yield reductions, as much as, 90% have been reported depending upon the type and intensity of weed flora (Massing *et al*. 2003, Sharma and Thakur 1998). Among herbicides, atrazine is widely used in maize because of its lower cost, broad-spectrum weed kill, application flexibility (pre-emergence or post-emergence), and compatibility with numerous herbicide mixtures (Walsh *et al*. 2012). However, the continuous use of atrazine is causing weed flora shift and evolution of resistance in weeds. Globally, 45 weed species across many corn growing areas have exhibited resistance against photosystem II (PSII) inhibitor herbicides, like atrazine (Heap 2019). This necessitates, having alternative modes of action herbicides in maize to decrease the probability of herbicide resistance evolution.

Mesotrione a p-hydroxyphenylpyruvate dioxygenase (HPPD) enzyme inhibitor controls the major annual broad-leaved weeds with lesser effect against grassy weeds (Armel *et al.* 2003a, Zhang *et al*. 2013). However, its dose varies depending on weed species. Mesotrione at 90 g/ha is needed for higher efficacy (95%) on barnyard grass {*Echinochloa crus-galli* (L.) Beauv}; but even higher doses are not effective against common purslane-*Portulaca oleracea* L. (Pannacci and Covarelli 2009). Mesotrione provides both pre- and post-emergence weed control (Bollman *et al*. 2006, Armel *et al*. 2003b). However, pre-emergence efficacy is affected by the soil and environmental conditions (Tapia *et al.* 1997), as well as, crop establishment methods, such as, no-till (Zhang *et al*. 2013) or conservation agriculture.

Mesotrione is also an alternative to control triazine resistant weeds like common lambsquarters *i.e. Chenopodium album* L. (Bollman *et al.* 2006). The HPPD- inhibitor herbicides are being preferred by maize growers due to their broad range of weed kill, flexible application timing, tank-mix herbicide compatibilities, and better crop tolerance (Walsh *et al.* 2012, Bollman *et al.* 2008). Atrazine and HPPD inhibitor herbicides also effectively control glyphosate resistant weeds (Sutton *et al.* 2002). Moreover, HPPD (mesotrione) and PS II inhibiting herbicides in the mixtures show synergism (Sutton *et al.* 2002, Abendroth *et al.* 2006). Synergistic herbicide mixture reduces the cost by saving time and dose and also provides the broad spectrum weed control. Furthermore, the usage of herbicides having independent modes of action in tank-mix combination rather than in rotation, drastically delay the inception of herbicide resistance evolution (Diggle *et al.* 2003, Zhang *et al.* 1995). Under Indian conditions, there is paucity of information regarding the effectiveness of mesotrione alone or in combination with atrazine in maize against prevalent weed flora. Thus, the studies were conducted with the objective to identify the effectiveness of mesotrione and mesotrione 2.27% + atrazine 22.72% w/w (Calaris Xtra 275 SC) combination against weeds in maize.

MATERIALS AND METHODS

Field evaluation of mesotrione and atrazine against weeds in maize

Field experiments were carried out during rainy *(Kharif)* seasons of 2013 and 2014 at Indian Institute of Wheat and Barley Research, Karnal, India in sandy clay loam soil having pH 8.2 and organic carbon content 0.39%. Seven weed control treatments (**Table 1**) evaluated were: atrazine at 1000 g/ha, 2,4-D-Na salt 1000 g/ha, mesotrione at 120 g/ha, untreated weedy control and ready-mix combination of atrazine plus mesotrione *i.e.* CalarisXtra 275 SC (mesotrione 2.27% + atrazine 22.72% w/w) at 750 (68+682), 875 (80+795) and 1000 (91+909) g *a.i.*/ha. Atrazine alone as pre-emergence (PE) was applied one day after sowing (DAS) and post-emergence (PoE) applications of 2,4-D-Na, mesotrione and atrazine plus mesotrione was made at 15 and 18 DAS during 2013 and 2014, respectively. Herbicides were applied with backpack sprayer having flat fan nozzles delivering 400 litre water/ha.

Treatments replicated thrice were tested in randomized block design. Maize hybrid- '*DKC 9108*' was sown during last week of June having 60 cm row to row spacing and 15-20 cm plant to plant spacing (approximately 20 kg/ha seed rate). Gap filling and thinning were done at 10-12 DAS to maintain uniform plant stand. Fertilizer (150 kg N, 26.2 kg P and 33.3 kg K/ha) and irrigation were applied according to recommended package of practice for maize. Phosphorus and potash were applied at sowing time. Nitrogen was applied in four splits, at sowing, around 4 leaf stage (20 DAS), knee high and tasseling stage. Weed dry weights (3 and 6 weeks after herbicide application) were recorded at two spots in each plot using a quadrat of 50 x 50 cm. Based on total weed dry weights, weed control efficiency (WCE) was calculated. The crop was manually harvested in the first week of October and shelling done using small plot maize sheller.

Pot experiment: Synergistic effect of mesotrione + atrazine against weeds

To determine the comparative efficacy of tank mix combination of mesotrione + atrazine, a pot experiment was conducted. The test species, crow footgrass {*Dactyloctenium aegyptium* (L.) Willd} and barnyard grass {*Echinochloa crus-galli* (L.) Beauv} were sown in the pots of 4.5 kg soil capacity at a depth of 0.5-1.0 cm and 2.0 cm, respectively. After germination, 15 and 25 plants/pot were maintained for herbicide spraying. Herbicides and their rates consisted of mesotrione at 30, 60 and 120 g/ha, atrazine 250, 500 and 1000 g/ha and their combination (mesotrione + atrazine) at 30 + 250, 60 + 500 and 120 + 1000 g/ha (**Figures 1** and **2**). Cationic surfactant (leader mix) at 1000 ml/ha was used with mesotrione and its combination with atrazine. Fresh biomass/pot was recorded 4 WAS and from which, the % biomass reduction compared to control was worked out for determining the herbicide response. For pot studies, completely randomized design (CRD) with 3-7 replications in three sets/runs of experimentation for each weed species was used.

Field experiment data were statistically analyzed in RCBD using Statistical Analysis System (SAS, version 9.2) and before the ANOVA, weed dry weight data were square root- transformed $(\sqrt{x+1})$. Based on the transformed data analysis, the letters were mentioned with original values in the table for result interpretation. The weed and crop data for both years were analysed separately because of the variations in weed intensity and diversity. Fisher's protected least significant difference (LSD) test at the p= 0.05 level was used for detecting differences among treatment means. For pot study, based on the data of different observations of three runs, average and ± SEM were worked out after calculating % biomass reduction.

RESULTS AND DISCUSSION

Herbicides evaluation against weeds in maize

Major weed flora of the experimental plots was: crow footgrass, *Dactyloctenium aegyptium* (L.)

Willd.; barnyard grass, *E. crus-galli*; large crabgrass, *Digitaria sanguinalis* (L.) Scop; horsepurslane, *Trianthema portulacastrum* L.; *Digera arvensis* Forsk. and *Phyllanthus niruri* L.. Among these weeds, *E. crus-galli*, *T. portulacastrum*, *D. arvensis* and *D. aegyptium* were dominant during both the years of studies.

Various herbicide treatments significantly affected the dry weight of major weeds (**Table 1** and **2**). The maximum total weed dry weight was in untreated weedy check and the values were 393.0 and 304.4 g/m^2 at 3 and 6 weeks after spray (WAS), respectively, during first year and 577.1 and 474.5 g/m^2 at 3 and 6 WAS, respectively during second year. Under untreated weedy control, *D. aegyptium*, *E. crus-galli*, *D. arvensis* and *T. portulacastrum*, had the dry weight of 92.5-363.4, 8.9-21.5, 34.8-51.4 and 137.2-223.8 g/m^2 at 3 WAS and the respective dry weight at 6 WAS ranged 149.8-324.1, 13.0-47.5, 44.4-92.2 and 33.9-36.2 g/m^2, respectively. *T. portulacastrum* dry weight was reduced by 73.6-84.9% at 6 WAS (33.9 and 36.2 g/m^2) compared to 3 WAS (223.8 and 137.2 g/m^2) mainly due to maturity because of its short life cycle. Balyan and Bhan (1986) had reported that *T. portulacastrum*, a short duration weed, starts production of flowers and seeds 20 to 30 DAS. Whereas, *E. crus-galli* dry weight increased at 6 WAS. Thus, during early stages *T. portulacastrum* and *D. aegyptium* were more competitive and at later stages, *E. crus-galli* was the competitive weed.

Mesotrione 120 g/ha applied alone was very effective in decreasing the dry weights of broad-leaved weeds namely *T. portulacastrum* and *D. arvensis*. However, it was poor against dominant grass weed *D. aegyptium*, as evident from weed dry weights data (**Tables 1** and **2**). In comparison to untreated control, mesotrione did not reduce the *D. aegyptium* biomass significantly and even, it was significantly higher during year 2013 at 3 WAS. Earlier studies (Armel *et al.* 2003a, Zhang *et al.* 2013) have also shown that mesotrione is more effective for control of broad-leaf weeds but less against grass weeds. The total weed dry weight under mesotrione were 199.5 and 347.6 g/m^2 at 3WAS during 2013 and 2014, respectively, whereas at 6 WAS, the respective values were 209.9 and 380.5 g/m^2 during 2013 and 2014.

The atrazine 1000 g/ha as PE application provided the good control of *D. arvensis* and was poor against *D. aegyptium*. The total weed dry weights data with atrazine application were 63.4 and 389.9 g/m^2 at 3 WAS during first and second year, respectively and 101.3 and 429.9 g/m^2 at 6 WAS during 2013 and 2014, respectively. Application of 2,4-D effectively controlled the broad-leaved weed *D. arvensis* but was relatively poor against *T. portulacastrum*. The grass weeds dry weights were greater in the mesotrione and 2,4-D treatments than in the weedy control (**Table 1** and **2**). This was due to the suppression of the grass weeds growth by broad-leaved weeds particularly *T. portulacastrum* in the untreated weedy control.

Table 1. Effect of herbicides on weeds in maize at 3 and 6 weeks after sowing in 2013

Treatments	Dose (g/ha)	Weed dry weight (g/m^2)							
		E. crus-galli	*Digera arvensis*	*D. aegyptium*	*Trianthema portulacastrum*	*Digitaria sanguinalis*	*P. niruri*	Other weeds	Total weeds
3 Weeks after sowing									
Untreated check	-	21.5 ^{A}	34.8 ^{A}	92.5 ^{C}	223.8 ^{A}	7.9 ^{AB}	1.7 ^{A}	10.9	393.0 ^{A}
Mesotrione + atrazine (1:10)- PoE	750	0.2 ^{B}	0.1 ^{C}	1.1 ^{E}	3.7 ^{C}	0.0 ^{C}	0.0 ^{B}	2.4	7.4 ^{D}
Mesotrione + atrazine (1:10)- PoE	875	0.1 ^{B}	0.1 ^{C}	0.2 ^{E}	0.2 ^{C}	0.0 ^{C}	0.0 ^{B}	0.4	0.9 ^{D}
Mesotrione + atrazine (1:10)- PoE	1000	0.1 ^{B}	0.1 ^{C}	0.1 ^{E}	0.2 ^{C}	0.0 ^{C}	0.0 ^{B}	1.9	2.4 ^{D}
Mesotrione- PoE	120	0.0 ^{B}	0.0 ^{C}	190.2 ^{B}	0.5 ^{C}	5.1 ^{B}	0.5 ^{B}	3.2	199.5 ^{B}
2,4-D- Na- PoE	1000	17.6 ^{A}	0.0 ^{C}	282.5 ^{A}	60.9 ^{B}	11.7 ^{A}	0.7 ^{B}	2.6	375.9 ^{A}
Atrazine pre-emergence at 1 DAS	1000	6.2 ^{B}	6.2 ^{B}	39.8 ^{D}	5.7 ^{C}	0.6 ^{C}	0.0 ^{B}	4.9	63.4 ^{C}
p-Value		0.0002	<0.0001	<0.0001	<0.0001	0.0001	0.0149	0.0606	<0.0001
6 Weeks after sowing									
Untreated check	-	47.5 ^{A}	44.4 ^{A}	149.8 ^{A}	33.9 ^{A}	23.8 ^{A}	0.1	5.1	304.4 ^{A}
Mesotrione +atrazine (1:10)-PoE	750	4.1 ^{C}	2.1 ^{C}	6.3 ^{C}	2.4 ^{B}	0.7 ^{B}	0.0	1.3	16.7 ^{D}
Mesotrione +atrazine (1:10)- PoE	875	2.4 ^{C}	1.6 ^{C}	1.4 ^{C}	0.3 ^{BC}	0.0 ^{B}	0.0	1.9	7.6 ^{D}
Mesotrione +atrazine (1:10)- PoE	1000	1.0 ^{C}	1.0 ^{C}	0.1 ^{C}	0.2 ^{BC}	0.0 ^{B}	0.0	1.6	4.0 ^{D}
Mesotrione- PoE	120	1.4 ^{C}	0.0 ^{C}	201.5 ^{A}	0.0 ^{C}	1.5 ^{B}	0.0	5.5	209.9 ^{B}
2,4-D- Na- PoE	1000	59.7 ^{A}	0.0 ^{C}	209.5 ^{A}	1.1 ^{BC}	14.3 ^{A}	0.0	0.0	284.5 ^{A}
Atrazine pre-emergence at 1 DAS	1000	22.5 ^{B}	10.1 ^{B}	52.6 ^{B}	1.0 ^{BC}	12.3 ^{A}	0.0	2.9	101.3 ^{C}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	0.0013	0.5440	0.2050	<0.0001

PoE = Post-emergence application at 15 DAS; Original values of weed dry weights data were square root transformed ($\sqrt{x+1}$) before statistical analysis and based on the analysis of the transformed data, letter have been assigned to original values for interpretation. Means with at least one letter common within a column are not statistically significant using Fisher's LSD at 5%

The ready mix combination (1:10 w/w) of mesotrione and atrazine at 750-1000 g/ha was more effective in decreasing the total weed dry biomass as compared to their alone applications. The reductions in weed infestation with ready mix combination at 875 and 1000 g/ha were significantly more compared to lower dose of 750 g/ha. The weed control efficiency (WCE) of ready mix combination of mesotrione and atrazine at 875 and 1000 g/ha was 97.5 and 98.7%, respectively, during 2013 whereas, during 2014, respective WCE was 88.9 and 92.1% (**Table 3**). However, sole application of mesotrione 120 g/ha and atrazine 1000 g/ha had lower WCE of 31.0 and 66.7%, respectively during first season and during second season, the corresponding values were 19.8 and 9.4%. The better efficacy in combination compared to alone application shows synergism in mixture. In earlier studies, the synergistic interactions between mesotrione and atrazine have been reported for control of many weeds (Bollman *et al.* 2008, Jhala *et al.* 2014, Johnson *et al.* 2002, Whaley *et al.* 2006, Woodyard *et al.* 2009, Abendroth *et al.* 2006). Janak and Grichar (2016) also reported the consistent annual grasses control including barnyardgrass (*E. crus-galli*) by three way combinations of S-metolachlor plus atrazine plus mesotrione than one active ingredient.

Weed control treatments also significantly (<0.0001) influenced the maize grain yield (**Table 3**). The uncontrolled weed competition during the crop duration resulted in the lowest grain yield of 4.76 and 3.73 t/ha in 2013 and 2014, respectively. Except, application of 2,4-D-Na 1000 g/ha, the rest of herbicide treatments (mesotrione, atrazine and their combinations) produced significantly higher grain yield compared with untreated weedy check. Grain

Table 2. Effect of herbicide treatments on weeds in maize at 3 and 6 weeks after sowing in 2014

Treatments	Dose (g/ha)	Weed dry weight (g/m^2)						
		Echinochloa crus-galli	*Digera arvensis*	*D. aegyptium*	*Trianthema portulacastrum*	*P. niruri*	Other weeds	Total weeds
3 Weeks after sowing								
Untreated check	-	8.9 ^{B}	51.4 ^{A}	363.4 ^{AB}	137.2 ^{A}	7.0 ^{A}	9.2 ^{BC}	577.1 ^{A}
Mesotrione + atrazine (1:10)-PoE	750	0.4 ^{C}	0.4 ^{C}	7.7 ^{C}	0.3 ^{D}	0.0 ^{B}	21.6 ^{AB}	30.5 ^{C}
Mesotrione + atrazine (1:10)- PoE	875	0.2 ^{C}	0.0 ^{C}	0.7 ^{C}	0.4 ^{D}	0.0 ^{B}	8.0 ^{BC}	9.2 ^{C}
Mesotrione + atrazine (1:10)- PoE	1000	0.1 ^{C}	0.0 ^{C}	0.9 ^{C}	0.4 ^{D}	0.0 ^{B}	6.8 ^{BC}	8.2 ^{C}
Mesotrione- PoE	120	0.7 ^{C}	0.0 ^{C}	340.5 ^{AB}	0.6 ^{D}	0.1 ^{B}	5.8 ^{BC}	347.6 ^{B}
2,4-D- Na- PoE	1000	11.8 ^{AB}	0.0 ^{C}	451.1 ^{A}	6.8 ^{C}	0.0 ^{B}	1.3 ^{C}	471.0 ^{AB}
Atrazine pre-emergence at 1 DAS	1000	13.8 ^{A}	19.2 ^{B}	281.0 ^{B}	41.8 ^{B}	0.0 ^{B}	34.1 ^{A}	389.9 ^{B}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0320	<0.0001
6 Weeks after sowing								
Untreated check	-	13.0 ^{AB}	92.2 ^{A}	324.1 ^{B}	36.2 ^{A}	0.6 ^{A}	8.5	474.5 ^{A}
Mesotrione + atrazine (1:10)-PoE	750	2.1 ^{C}	5.5 ^{C}	53.1 ^{C}	4.1 ^{C}	0.2 ^{B}	12.3	77.3 ^{B}
Mesotrione + atrazine (1:10)- PoE	875	2.0 ^{C}	1.3 ^{C}	37.4 ^{C}	1.9 ^{CD}	0.1 ^{B}	9.8	52.5 ^{B}
Mesotrione + atrazine (1:10)- PoE	1000	1.8 ^{C}	1.1 ^{C}	24.9 ^{C}	1.3 ^{CD}	0.1 ^{B}	8.2	37.4 ^{B}
Mesotrione- PoE	120	0.0 ^{C}	0.0 ^{C}	379.1 ^{AB}	0.0 ^{D}	0.0 ^{B}	1.4	380.5 ^{A}
2,4-D- Na- PoE	1000	5.0 ^{BC}	0.0 ^{C}	423.1 ^{A}	0.9 ^{CD}	0.0 ^{B}	17.1	446.1 ^{A}
Atrazine pre-emergence at 1 DAS	1000	14.9 ^{A}	63.2 ^{B}	320.8 ^{B}	17.9 ^{B}	0.0 ^{B}	13.0	429.9 ^{A}
p-Value		0.0049	<0.0001	<0.0001	<0.0001	0.0018	0.8843	<0.0001

PoE = Post-emergence application at 18 DAS; Original values of weed dry weights data were square root transformed ($\sqrt{x+1}$) before statistical analysis and based on the analysis of the transformed data letter have been assigned to original values for interpretation. Means with at least one letter common within a column are not statistically significant using Fisher's LSD at 5%.

Table 3. Weed control efficiency and maize grain yield as influenced by herbicides during 2013 and 2014

Herbicide	Dose (g/ha)	Time of application (DAS)		Weed control efficiency (WCE) % at 6 WAS		*Grain yield (t/ha)	
		2013	2014	2013	2014	2013	2014
Untreated check	-	-	-	0.0	0.0	4.76 ^{D}	3.73 ^{C}
Mesotrione + atrazine	68+682 (750)	15	18	94.5	83.7	7.55 ^{A}	7.73 ^{A}
Mesotrione + atrazine	80+795 (875)	15	18	97.5	88.9	7.74 ^{A}	8.11 ^{A}
Mesotrione + atrazine	91+909 (1000)	15	18	98.7	92.1	7.76 ^{A}	8.00 ^{A}
Mesotrione	120	15	18	31.0	19.8	5.96 ^{C}	5.83 ^{B}
2,4-D- Na	1000	15	18	6.5	6.0	5.30 ^{CD}	3.82 ^{A}
Atrazine	1000	01	01	66.7	9.4	6.70 ^{B}	5.93 ^{B}
p-Value						<0.0001	<0.0001

*Means with at least one letter common within a column are not statistically significant using Fisher's LSD at 5%; DAS - Day after sowing; WAS Week after sowing yields obtained in 2,4-D-Na (5.30 and 3.82 t/ha) and weedy check (4.76 and 3.73 t/ha) were not statistically different due the failure of 2,4-D-Na in controlling dominant grass weeds. Ready mix combination at 875-1000 g/ha applied as early PoE provided better yield (7.74-8.11 t/ha) compared to the lowest dose of 750 g/ha, untreated control, mesotrione 120 g/ha (5.83-5.96 t/ha), atrazine 1000 g/ha (5.93-6.70 t/ha) and 2,4-D-Na 1000 g/ha. However, grain yield under various doses of ready mixture was statistically similar but significantly better than mesotrione 120 g/ha, 2,4-D 1000 g/ha and atrazine 1000 g/ha. The improved yield was as a resultant of better broad spectrum weed control (grass and broad-leaved weeds) in herbicide mix combinations. Janak and Grichar (2016) also observed higher corn yield when herbicide treatments consisted of more than one active ingredient compared to single active ingredient. Moreover, this strategy of using ready mix combination of mesotrione + atrazine will help in delaying the herbicide resistance evolution as well as managing the problem of weed flora shift.

Synergistic effect of mesotrione + atrazine against weeds in pot studies

Mesotrione (30, 60 and 120 g/ha) and atrazine (250, 500 and 1000 g/ha) alone and in tank-mix combinations at 30 + 250, 60 + 500 and 120 + 1000 g/ha were evaluated on two grass weeds (*E. crus-galli* and *D. aegyptium*). Mesotrione and atrazine applied alone were poor in reducing the fresh biomass of both weeds compared to their combinations (**Figure 1**). The biomass reductions of *D. aegyptium* with application of mesotrione at 30, 60 and 120 g/ha with cationic surfactant (1000 ml/ha) were 49.9, 63.7 and 90.7%, respectively, compared to untreated control and with applications of atrazine 250, 500 and 1000 g/ha were 47.2, 64.8 and 83.5%, respectively. However, the tank mix combinations of mesotrione + atrazine 30 + 250, 60 + 500 and 120 + 1000 g/ha with surfactant caused respective *D. aegyptium* biomass reductions of 85.5, 96.5 and 99.3%. Similarly, the *E. crus-galli* fresh weight reductions with application of mesotrione at 30, 60 and 120 g/ha were 51.8, 83.5 and 93.7%, respectively (**Figure 1**). The applications of atrazine at 250, 500 and 1000 g/ha caused respective fresh weight reductions of 47.9, 79.1 and 88.9%. The combinations of mesotrione + atrazine 30 + 60, 60 + 500 and 120 + 1000 g/ha with 1000 ml/ha surfactant reduced the *E. crus-galli* fresh weight by 96.2, 98.6 and 100%, respectively. These pot studies results confirmed mesotrione plus atrazine synergism for weed control.

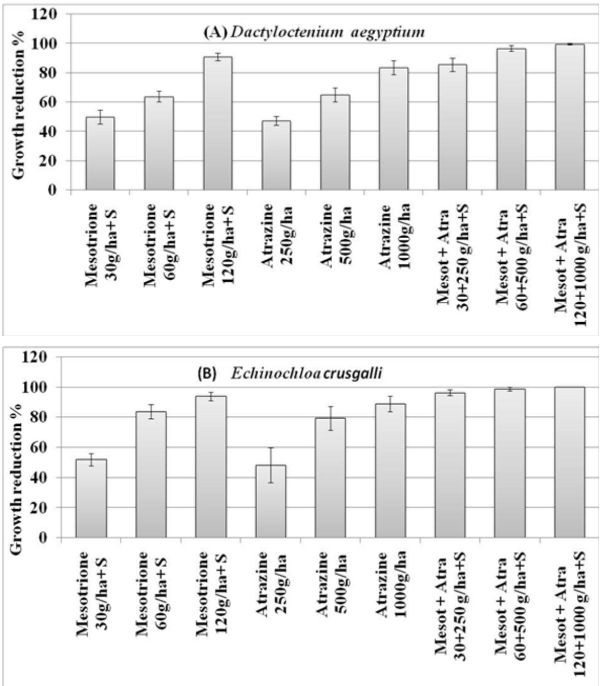

Figure 1. Fresh biomass reduction of (A) *Dactyloctenium aegyptium* and (B) *E. crus-galli* with application of mesotrione, atrazine and their combinations at various doses. Vertical error bars above means represent ±SEM. S - Surfactant

As compared to field studies, pot studies have shown better efficacies of mesotrione against grass weeds, as the external cationic surfactant (1000 ml/ha), was not added in field studies. Earlier results (Young *et al.* 2007, Chhokar *et al.* 2015) demonstrated that HPPD herbicides (mesotrione, tembotrione and topramezone) had good weed control efficacy, when applied as tank-mix with methylated seed oil (MSO) adjuvant. Therefore, further studies are needed to evaluate the effect of surfactant or adjuvant on mesotrione efficacy. In earlier studies, nitrogen enhanced the smooth crabgrass (*Digitaria ischaemum*) control with mesotrione and topramezone (Elmore *et al.* 2012). The ammonium sulphate (AMS) addition also enhanced the mesotrione efficacy (Devkota *et al.* 2016).

Since, mixtures of two or more herbicides can give more reliable control of some hardy weeds and reduce the risk of evolving herbicide resistance even with the application of lower amount of total herbicides (Zhang *et al.* 1995). Similarly, synergism resulted on the atrazine resistant (AR) velvetleaf biotype, when a constant rate of mesotrione 3.2 g/ha was tank mixed with atrazine (126 to 13,440 g/ha). Also, addition of mesotrione 1.5 g/ha enhanced the resistant wild radish (*Raphanus raphanistrum*) population control by a further 60% in mixture with atrazine 400 g/ha (Walsh *et al*. 2012) indicating the synergistic herbicide interactions in overcoming the target-site herbicide resistance mechanism.

It was concluded that ready mix combination (1:10 w/w) of mesotrione + atrazine at 875-1000 g/ha can be used for effective broad spectrum (grass and broad-leaf) weed management in maize. The atrazine and mesotrione mixture was synergistic in controlling weeds and was significantly better than the alone usage of atrazine 1000 g/ha and mesotrione 120 g/ha. Weed management strategies involving more than one herbicide mechanism of action are important in managing herbicide-resistant weeds and economic maize production. However, for long term sustainable and economic weed management, proper attention have to be given by integration of non-chemical weed control practices with diverse herbicide modes of actions.

REFERENCES

Abendroth JA, Martin AR and Roeth FW. 2006. Plant response to combinations of mesotrione and photosystem II inhibitors. *Weed Technology* **20**: 267–274.

Armel GR, Wilson HP, Richardson RJ and Hines TE. 2003a. Mesotrione combinations for postemergence control of Horsenettle (*Solanum carolinense*) in corn (*Zea mays*). *Weed Technology* **17**(1): 65–72.

Armel GR, Wilson HR, Richardson RJ and Hines TE. 2003b. Mesotrione, acetochlor, and atrazine for weed management in corn. *Weed Technology* **17**: 284–290.

Balyan RS and Bhan VM. 1986. Emergence, growth, and reproduction of Horse Purslane (*Trianthema portulacastrum*) as influenced by environmental conditions. *Weed Science* **34**(4): 516–519.

Bollman JD, Boerboom CM, Becker RL and Fritz VA. 2008. Efficacy and tolerance to HPPD-inhibiting herbicides in sweet corn. *Weed Technology* **22**(4): 666-674.

Bollman SL, Kells JJ and Penner D. 2006. Weed response to mesotrione and atrazine applied alone and in combination pre-emergence. *Weed Technology* **20**: 903–907.

Chhokar RS, Sharma RK and Sharma I. 2015. Improving the herbicide efficacy with tank mix adjuvant usage. *Pestology* **39**(5): 15–34.

Devkota P, Spaunhorst DJ and Johnson WG. 2016. Influence of carrier water pH, hardness, foliar fertilizer, and ammonium sulfate on mesotrione efficacy. *Weed Technology* **30**(3): 617–628.

Diggle AJ, Neve PB and Smith FP. 2003. Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. *Weed Research* **43**: 371–382.

Elmore MT, Brosnan JT, Kopsell DA and Breeden GK. 2012. Nitrogen-enhanced efficacy of mesotrione and topramezone for smooth crabgrass control. *Weed Science* **60**(3): 480–485.

Heap I. 2019. The International survey of herbicide resistant weeds. Available from URL: http://weedscience.org/, Accessed date: 26 February 2019.

Janak TW and Grichar WJ. 2016. Weed control in corn (*Zea mays* L.) as influenced by pre-emergence herbicides. *International Journal of Agronomy*, Article ID 2607671, 9 pages http://dx.doi.org/10.1155/2016/2607671.

Jhala AJ, Sandell LD, Rana N, Kruger GR and Knezevic SZ. 2014. Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant palmer amaranth (*Amaranthus palmeri*) in Nebraska. *Weed Technology* **28**(1): 28–38.

Johnson BC, Young BG and Matthews JL. 2002. Effect of post-emergence application rate and timing of mesotrione on corn (*Zea mays*) response and weed control. *Weed Technology* **16**: 414–420.

Massing RA, Currie RS and Trooien TP. 2003. Water use and light interception under Palmer amaranth and corn competition. *Weed Science* **51**: 523–531.

Pannacci E and Covarelli G. 2009. Efficacy of mesotrione used at reduced doses for post-emergence weed control in maize (*Zea mays* L.). *Crop Protection* **28**: 57–61.

Sharma V and Thakur DR. 1998. Integrated weed management in maize under mid-hill conditions of North-Western Himalayas. *Indian Journal of Weed Science* **30** (3, 4): 158–162.

Sutton P, Richards C, Buren L and Glasgow L. 2002. Activity of mesotrione on resistant weeds in maize. *Pest Management Science* **58**: 981–984.

Tapia LS, Bauman TT, Harvey RG, Kells JJ, Kapusta G, Loux MM, Lueschen WE, Owen MDK., Hageman LH and Strachan SD. 1997. Post-emergence herbicide application timing effects on annual grass control and corn (*Zea mays*) grain yield. *Weed Science* **45**: 138–143.

Walsh MJ, Stratford K, Stone K and Powles SB. 2012. Synergistic effects of atrazine and mesotrione on susceptible and resistant wild radish (*Raphanus raphanistrum*) populations and the potential for overcoming resistance to triazine herbicides. *Weed Technology* **26**(2): 341–347.

Whaley CM, Armel GR, Wilson HP and Hines TE. 2006. Comparison of mesotrione combinations with standard weed control programs in corn. Weed Technology **20**(3): 605–611.

Woodyard AJ, Hugie JA and Riechers DE. 2009. Interactions of mesotrione and atrazine in two weed species with different mechanisms for atrazine resistance. *Weed Science* **57**(4): 369–378.

Young BG, Zollinger RK and Bernards ML. 2007. Variability of tembotrione efficacy as influenced by commercial adjuvant products. *North Central Weed Science Society Proceeding* **62**: 141.

Zhang J, Hamill AS and Weaver SE. 1995. Antagonism and synergism between herbicides: trends from previous studies. *Weed Technology* **9**: 86–90.

Zhang J, Zheng Li, Jäck O, Yana D, Zhang Z, Gerhards R and Ni H. 2013. Efficacy of four post-emergence herbicides applied at reduced doses on weeds in summer maize (*Zea mays* L.) fields in North China Plain. *Crop Protection* **52**: 26–32.