Indian Journal of Agronomy **67** (2): 158–164 (June 2022)

Research Paper

Efficacy of p-hydroxy-phenyl-pyruvate dioxygenase (HPPD) enzyme-inhibitive tembotrione and topramezone herbicides for weed-management in rainy season grain sorghum (*Sorghum bicolor*)

ARVIND VERMA[1], B. GANGAIAH[2] AND V.A. TONAPI[3]

All India Coordinated Sorghum Improvement Project, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan 313 002

Received: May 2021; Revised accepted: March 2022

ABSTRACT

A field experiment was conducted during the rainy season (*kharif*) of 2019 and 2020 at Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, to ascertain the weed-management efficacy of post-emergence (PoE) tembotrione and topramezone at 25 days after sowing following pre-emergence (PE) atrazine in the *kharif* grain sorghum [*Sorghum bicolor* (L.) Moench]. Eight treatments (6 herbicidal along with weed-free and weedy check) were evaluated in randomized block design (RBD) with 3 replications. Results showed that, uncontrolled weeds have inflicted a grain, stover yield and net income penalty of 63.7, 55.5 and 69% over weed-free check (3.47, 12.34 t/ha and ₹135,216). Pre-emergence (PE) application of atrazine @ 0.5 kg a.i./ha was found to be the most promising herbicide in terms of benefit: cost ratio (5.76) despite having 12.4, 6.2, and 6.71% lower grain, stover and net income than weed-free treatment (5.03). Both PE and PoE application of atrazine did not bring any yield and profit gains over its PE application. Topramezone and tembotrione (PoE) controlled weeds as effective as weed-free treatment and their impacts persisted up to crop maturity. However, on account of crop phytotoxicity that is dependent on dose (2.83–5.17) severe yield losses (60 and 51.9% grain and stover) were recorded. Both tembotrione and topramezone at their higher dose (0.0242 and 0.0363 kg a.i./ha) resulted in at par grain yield (1.18 t/ha) as weedy check (1.26 t/ha).

Key words: Herbicide efficiency index, Net income, Phytotoxicity, Sorghum, Tembotrione, Topramezone, Weed Index

Rajasthan is India's leading nutricereal producer, accounting for 26.54 (5.84 million ha) and 16.44% (7.06 million tonnes) of total area and production in 2018–19 (DoES, 2019), respectively. Sorghum accounts for 9.66 and 6.66% area and output. Rajasthan ranks third and fourth in terms of area (0.56 m ha) and production (0.47 m t), but it ranks last in terms of productivity (832 kg/ha), with only Maharashtra (617 kg/ha) being lower. These grain yield of state were 15.0% lower than mean yield of country (979 kg/ha, DoES, 2019) and is 74.9% lower than estimated potential yield (3.31 t/ha) of the rainy (*kharif*) season (Murty *et al.,* 2007). This low productivity was ascribed to its rainfed cultivation (only 0.4% of total area is irrigated in 2015–16, DoES, 2019) and associated intense biotic and abiotic pressures. Weeds are the most notable biotic stress (Mishra and Talwar, 2020), since they deplete the valuable soil moisture (Dalley *et al.,* 2006) and nutrients (Mishra *et al.,* 2014) that would otherwise be used for crop production. AICRP weed management trials (39 number) spread across 3 sorghum-growing states; Karnataka, Maharashtra and Madhya Pradesh indicated a 25.1% weed-associated yield losses (Gharde *et al.,* 2018). These losses were attempted to minimize by cultivators through mechanical interculture and manual hand-weeding operations. However, there was 24.43% decline in draught animals between 2012 (74.02 million) and 2019 (Livestock Census data of India). Further, there is a 17.05% decline manual work force employed in agriculture between 2000 and 2019 as per ILOSTAT data base of World bank. Thus, animal-drawn mechanical and manual weeding operations have become less possible options of weed management and thus there is a rapid shift towards use of herbicides for weed management. Among herbicides, atrazine (Sharma *et al.,* 2000) with broad window of application (pre- and post-emergence) has become part of weed management in sole

[2]**Corresponding author's Email:** gangaiah@millets.res.in
[1]Professor, AICSIP (Agronomy and Physiology), MPUAT, Udaipur, Rajasthan 313 002, [2]Principal Scientist (Agronomy); [3]Director, ICAR-IIMR, Rajendranagar, Hyderabad, Telangana 500 030

sorghum crop. However, its ineffectiveness against few weeds (Walia *et al.,* 2007) and development of resistance with repeated use (Heap, 2020) has led to development of p-hydroxy-phenyl-pyruvate dioxygenase (HPPD) enzyme-inhibitive post-emergent herbicides (Topramezone and Tembotrione) with broad-spectrum weed control, flexible application times, tank-mix compatibilities, better crop safety (Singh *et al*., 2012) with ability to control triazine-resistant weeds (Kohrt and Sprague, 2017) in maize. Looking at success of these herbicides in maize, current study was planned under All India Coordinated Sorghum Improvement Project (AICSIP) to assess the utility of these 2 HDDP herbicides to rainy season (*kharif*) grain sorghum weed management.

MATERIALS AND METHODS

A field experiment was conducted during the rainy [*kharif* (July-October) seasons] of 2019 and 2020 at All India Coordinated Sorghum Improvement Project centre at Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan. The experimental site was situated at 24° 35' N, 73° 42' E at an altitude of 579.5 m above mean sea-level.

The experimental non-saline (electrical conductivity : 0.76 dS/m) alkaline (8.1 *p*H) sandy clay loam soil was rated as medium for organic carbon (0.61%), available N and K (286.4 and 354.4 kg/ha) and high for available P (21.2 kg/ha) in plough-layer based on soil samples drawn before start of study on mean basis. The experiment comprising 8 weed-management treatments [(Atrazine 50 WP @ 0.50 kg a.i/ha, pre-emergence, PE (Control; T_1), T_1 + atrazine 50 WP @ 0.50 kg a.i/ha, post-emergence (PoE) at 20 days after sowing (DAS), T_1 + topramezone 33.6 SC @ 0.0126 kg a.i/ha, PoE at 25 DAS; T_1 + tembotrione 34.4 SC @ 0.0242 kg a.i/ha, PoE at 25 DAS; T_1, + topramezone 33.6 SC @ 0.0189 kg a.i./ha, PoE at 25 DAS; T_1 + tembotrione 34.4 SC @ 0.0363 kg a.i/ha, PoE at 25 DAS; weed-free (hand-weeding at 15 and 35 DAS and weedy check)] was laid out in randomized complete block design (RCBD) with 3 replications. Sorghum 'CSH 25'seeds were dibbled in rows and planted at 45 and 15 cm apart on 8 July, 2019 and 10 July 2020, respectively. Recommended dose of fertilizers (80 : 16.7 : 27 kg N : P : K/ha) were used for the crop. Entire dose of P and K along with 30 kg N in the form of diammonium phosphate, muriate of potash and urea, respectively, were broadcast applied in the last ploughing prior to sowing. Remaining N was top-dressed in 2 equal splits on 20 and 35 DAS following hand-weeding. Recommended package of practices of university were followed for raising rain fed sorghum crop that was harvested on 18 October 2019 and 2 November 2020. Application of herbicides was done as per treatment using 500 litres of spray fluid. Atrazine was used pre-and post-emergence (PoE) immediately after sowing and at 20 DAS, while HPPD herbicides were applied at 25 DAS. A rainfall of 961.8 and 836.1 mm was received in during 2019 and 2020 crop cycle, and crop did not face any moisture stress.

Data on weed population species-wise (number/m^2) were recorded at 30, 60 DAS (2019) and 20, 40 DAS (2020) and at harvesting (2019 and 2020) at 3 quadrants of 0.5 m × 0.5 m/plot. These weeds were categorized as monocots and dicots and their dry weight were recorded. Data on weed density and weed dry weight were subjected to $\sqrt{\times + 0.5}$ transformation prior to analysis. Weed-control efficiency (WCE, %), herbicide-efficiency index (HEP) and weed index (WI) were calculated as:

$$\text{WCE (\%)} = \frac{\text{Weed dry weight in weedy check–weed dry weight of a treatment}}{\text{weed dry weight in weedy check}} \times 100$$

$$\frac{\text{Grain yield in herbicide treatment – Grain yield in weedy check} \times 100}{\text{Grain yield in weedy check}}$$

$$\text{HEI} = \frac{\text{weed dry matter in herbicide treatment}}{\text{weed dry matter in weedy check}} \times 100$$

$$\text{WI} = \frac{\text{Grain yield in weed-free plot – grain yield from a treatment plot}}{\text{Grain yield from weed-free plot}} \times 100$$

The observations of phytotoxicity on sorghum plants were made on the basis of phytotoxicity-rating scale (PRS) for the applied herbicides at 3, 6, 9 and 12 days after treatment (DAT). The parameters on phytotoxicity taken were leaf epinasty and hyponasty, necrosis (leaf tips and margins) and wilting. The observation on the level of phytotoxicity through visual assessment of crop response was rated on 0–10 scale (0, no adverse effect of herbicide and 10, 100% adverse effect of herbicide on sorghum). Data on growth, yield attributes were recorded from 5 randomly selected plants, while yield on net plot basis at harvesting. For economics, prevailing market price of inputs and minimum support price of grain (₹26.4/kg) and stover (₹6.25/kg) were used. As similar trend of results was observed during 2019 and 2020 for all the characters, hence pooled analysis was done. Year and treatment impacts were significant while their interaction were not significant, hence, mean data for years were also presented. All the parameters were subjected for statistical analysis and interpretation as per Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Weed flora

The experimental field was invaded by monocot and dicot weeds during both the years of study. Awnless barnyard grass [*Echinochloa colona* (L.) Link], tropical spiderwort (*Commelina benghalensis* L.), green foxtail grass [*Setaria glauca* (L.) Samp.], and viper grass [*Dinebra retroflexa* (Vahl) Panz.] formed the monocot weed flora, while false amaranth [*Digeria muricata* (L.) Mart.], giant pigweed (*Trianthema portulacastrum* L. and sunnberry *(Physalis lagascae* Roem. & Schult.*;* syn. *minima* L.) is the dicot weed flora in the experiment.

Weed density, weed dry weight and weed control efficiency

Weed density (dry weight) data of the weedy check treatment revealed that, monocots were dominant, as evident from 78.2 (80.7%) of their share in total (monocot + dicot) density (weight) during 2020 (mean of 20, 40 DAS and harvesting). Data indicate that, monocot weed density (weight) varied from 58.62 (28.70), 82.13 (52.76) and 102.94 (89.63) at 20, 40 DAS and harvesting as against the total weed density (weight) 73.39 (34.71), 107.07 (67.52) and 132.18 (111.35) during 2020 (Table 1). During 2019, monocot weed density (number/m^2) varied from 79.2 and 108.96 out of 104.8 and 144.24 total weed density recorded at 30 and 60 DAS, while at harvesting, monocots accounted for 75.2 (77.8%) of total density of 129.4 (137.1 weed weight).

Transformed weed density and weed dry weight data (Table 1) at 20 DAS (2020) showed that atrazine (PE) application has effectively managed diverse sorghum weed flora. This is evident from the fact that there was 47.3 and 47.6% lower weed density and weed weight values (4.53 and 3.11 g/m^2) in atrazine (PE) treatments than the weedy check (8.60 and 5.93 g/m^2). However, atrazine (PE) treatments resulted in markedly higher weed density and weed weight values than the weed-free treatment (2.34 and 1.66 g/m^2). In weed-free treatment, though 1 hand-weeding was done at 15 DAS, few weeds that remained un-removed and those emerged in next 5 days' time prior to observation of 20 DAS have led to the above positive weed density (weed dry weight) values. Data of 30 DAS (2019) indicated that, atrazine (PoE) application caused 16.4% (7.8%) reduction in weed density (weed dry weight) compared to atrazine (PE). Due to the emergence of new weeds, the impact of atrazine (PoE) on weed density dropped to 7.44% by 40 DAS observation (2020), whereas weed weights remained constant at 7.43% (PE). Pooled data at harvesting stage also showed superiority of atrazine (PoE) application with 7.79% (7.97%)

Table 1. Effect of pre-and post-emergence herbicides on weed density and weed dry weight and weed-control efficiency (%) in sorghum (pooled data: 2019 and 2020)

Treatment	Weed density (no./m^2)					Dry weight of weeds (g/m^2)			Weed-control efficiency (%)		
	30 DAS (2019)	20 DAS (2020)	60 DAS (2019)	40 DAS (2020)	At harvesting (pooled)	20 DAS (2020)	40 DAS (2020)	At harvesting (pooled)	20 DAS (2020)	40 DAS (2020)	At harvesting (pooled)
Atrazine @ 0.50 kg a.i./ha (PE): T_1	5.62	4.53	6.32	5.11	06.16	3.12	4.04	05.52	73.42	76.57	75.85
T_1 + atrazine as PoE at 20 DAS	4.70	4.44	5.47	4.73	05.68	3.09	3.74	05.08	74.00	79.98	79.46
T_1 + topramezone @ 0.0126 kg a.i./ha (PoE, 25 DAS)	3.22	4.32	4.07	3.18	04.47	2.97	2.56	04.11	76.10	90.98	86.73
T_1 + tembotrione @ 0.0242 kg a.i./ha (PoE, 25 DAS)	3.90	4.46	4.32	2.88	04.02	3.06	2.34	03.71	74.39	92.56	89.26
T_1 + topramezone @ 0.0189 kg a.i./ha (PoE, 25 DAS)	2.42	4.70	2.77	2.35	02.94	3.23	1.91	02.69	71.41	95.33	94.48
T_1 + tembotrione @ 0.0363 kg a.i./ha (PoE, 25 DAS)	2.67	4.72	3.07	2.43	03.28	3.21	1.95	02.98	71.71	95.13	93.16
Weed-free (hand-weeding at 15 and 35 DAS)	3.57	2.34	4.21	2.34	04.09	1.66	1.85	03.68	93.44	95.68	89.44
Weedy check	10.26	8.60	12.03	10.37	12.33	5.93	8.25	11.15	-	-	-
CD (P=0.05)	0.205	0.313	0.225	0.323	0.312	0.202	0.247	0.236	3.804	2.08	1.354
2019					4.95			4.59			76.57
2020					5.79			6.03			75.53
CD (P=0.05)					0.156			0.118			0.677

DAS, Days after sowing; PE, pre-emergence; PoE, post-emergence

[$\sqrt{X+0.5}$]

lower weed density (weed dry weight) than atrazine (PE). Topramezone and tembotrione (PoE, 25 DAS) application impacts were seen within 5 days of their application, as evident from 30 DAS observation (2019). Weed density (weed dry weight) recorded with higher dose of topramezone (0.0189 kg a.i./ha) and tembotrione (0.0363 kg a.i./ha) were markedly lower than that of hand-weeded treatment at 15 DAS. At 40 DAS during 2020 (60 DAS, 2019) and at harvesting on pooled basis, topramezone (0.0189 kg a.i./ha) and tembotrione (0.0363 kg a.i./ha) continued its superiority to weed-free treatment for lower weed density/weed weight. In general, weed density (weed dry weight) of 2019 season at harvesting was 14.5 (23.9%) lower than that of 2020 (5.79 and 6.03).

Weed-control efficiency (WCE) at 20 DAS indicated that, atrazine (PE) has a mean WCE of 73.5% as against 93.5% of hand-weeded treatment at 15 DAS. Atrazine (PoE) resulted in 3.41 and 3.61% higher WCE than atrazine (PE) at 40 DAS (2020) and at harvesting on pooled basis (76.57 and 75.85%). Tembotrione and topramezone (PoE) increased WCE values of atrazine (PE), i.e. 73.5% to 92.2% (93.5 and 90.9% at 40 DAS and harvesting; mean over 2 doses) that were 12.5% higher than atrazine (PE + PoE) WCE value (79.7%). Both tembotrione and topramezone at their higher dose of application (0.0363 and 0.0189 kg a.i./ha) showed at par and markedly higher WCE values as that of weed-free treatment at 40 DAS and harvesting stage, respectively, indicating their prolonged effectiveness.

Relative efficacy of herbicides against monocot and dicot weeds

Weed dry weight data (Table 2) of 2020 at 20 DAS showed that atrazine (PE) has brought down the monocot and dicots weed weight by 76.7 and 58.2% compared with that of weedy check (28.7 and 6.01 g/m^2). However, the mean dry weight of monocot and dicot in PE atrazine (6.69 and 2.51 g/m^2) treatment, was 4.15 and 3.75 times higher than that of weed-free treatment (1.61 and 0.61 g/m^2). Atrazine (PoE) has brought an additional 23.7% reduction in monocot weed dry weight, while dicot weed weights remained unchanged over atrazine (PE) at 40 DAS and harvesting (11.74 and 18.87 g/m^2). Tembotrione and topramezone (PoE) at their higher dose (0.0363 and 0.0189 kg a.i./ha) resulted in significantly lower weed weights of monocot than weed-free treatment, whereas dicot weed weights (at 40 DAS and at harvest) were comparable to weed-free treatment. Topramezone (PoE) at its lower dose (0.0126 kg a.i./ha) stood at par with weed-free situation for both monocot (harvesting) and dicot weed weights (40 DAS and harvesting). Further, topramezone and tembotrione at their lower dose have markedly higher monocot weed dry weights than weed-free treatment at 40 DAS. This means that both dicot and monocot weeds were effectively suppressed from the time they were applied on 25 DAS until the crop reached maturity. For dicots and monocots (Fig. 1), the lower weed weights are reflected in significantly higher WCE values than the weed-free treatment (Fig. 1).

Growth and yield attributes

Pooled data on growth and yield attributes of sorghum as influenced by weed management treatments are given in Table 3. Except for tembotrione (0.0363 kg a.i./ha) and weed-free treatments, which were comparable to weedy check, weedy check has recorded the shortest plants.

Table 2. Monocot and dicot weed dry weight as influenced by pre-and post-emergence herbicides use in sorghum

Treatment	At 20 DAS		At 40 DAS		At harvesting	
	Monocots	Dicots	Monocots	Dicots	Monocots	Dicots
Atrazine @ 0.50 kg a.i./ha (PE): T_1	6.80	2.43	11.74	4.11	18.87	6.55
T_1 + atrazine as PoE at 20 DAS	6.50	2.52	8.96	4.55	16.43	7.24
T_1 + topramezone @ 0.0126 kg a.i./ha (PoE, 25 DAS)	6.22	2.08	4.75	1.34	9.68	3.36
T_1 + tembotrione @ 0.0242 kg a.i./ha (PoE, 25 DAS)	6.71	2.18	4.43	0.60	8.57	1.82
T_1 + topramezone @ 0.0189 kg a.i./ha (PoE, 25 DAS)	6.97	2.96	2.48	0.68	4.76	1.99
T_1 + tembotrione @ 0.0363 kg a.i./ha (PoE, 25 DAS)	6.91	2.91	2.62	0.67	6.34	2.04
Weed-free (hand-weeding at 15 and 35 DAS)	1.61	0.67	1.66	1.25	6.33	2.99
Weedy check	28.70	6.01	53.36	14.16	89.63	21.72
CD (P=0.05)	1.039	0.453	1.793	0.497	3.461	0.647

DAS, Days after sowing; PE, pre-emergence; PoE, post-emergence
(g/m^2, $\sqrt{x + 0.5}$)

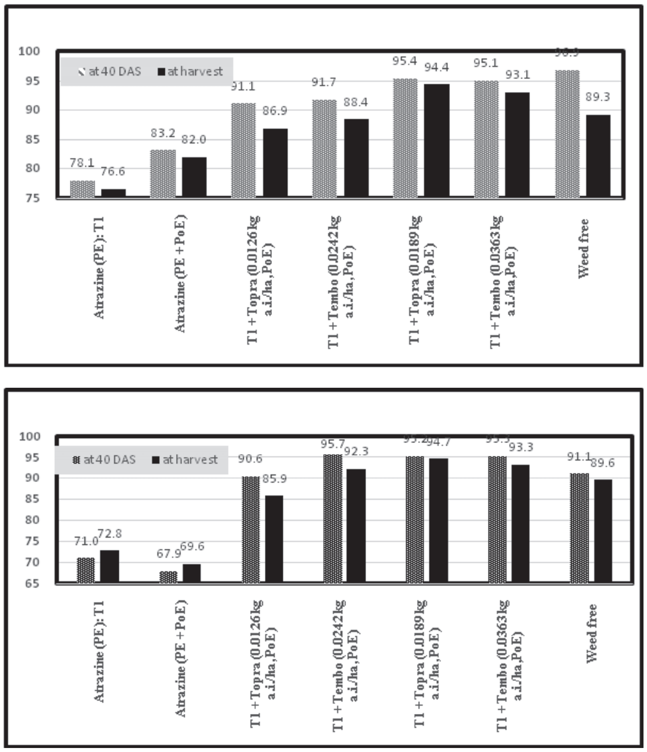

Fig. 1. Monocot (top) and dicot (bottom) weed-control efficiency (%) as influenced by post-emergence herbicides use in sorghum

Grains/panicle were significantly reduced (19.9%) by higher dose of topramezone (0.0189 kg a.i./ha) and with both lower and higher doses (0.0243 and 0.0363 kg a.i./ha) of tembotrione (9.6 and 25.4%) compared to weedy check (2423). Panicles/m^2 were found least (8.78) with tembotrione (0.0363 kg a.i./ha) being at par with topramezone @ 0.0189 kg a.i./ha (9.03) and tembotrione @ 0.0243 kg a.i./ha (9.47). Topramezone @ 0.0126 kg a.i./ha exhibited best values (11.47). Atrazine (PE) revealed at par panicles/m^2 as weed-free treatment (17.11) and uncontrolled weeds (weedy check) resulted reduction in panicle production by 17.5% in weed-free treatment. Seed index (100-seed weight) was reduced by 6.4 and 12.4% with HPPD herbicides use (mean of 2 doses) than weed-free treatment (3.35 g) and this reduction was significant. These dose-dependent reductions in grains/panicle, seed weight, and panicles/m^2 compared with weed-free treatment with HPPD herbicides imply dose-dependent phytotoxicity. Weed-free treatment stood distinctly superior for number of grains/panicle to all other treatments. Increased moisture and nutrients supplies to sorghum crop in absence of weeds increased the yield attributes in atrazine (PE, PoE) and weed-free treatments over weedy check. On phytotoxicity scale, topramezone stood a step lower (2.83 and 4.67) to tembotrione (3.83 and 5.17) at low and high dose respectively. The phytotoxicity reported in this study support the findings of Dan *et al*., (2010) and Takano *et al*., (2016).

Grain and stover yield

Grain and stover yields (t/ha) of sorghum as influenced by weed management treatments are given in Table 3. In rainy season grain sorghum, uncontrolled weeds reduced

Table 3. Effect of pre-and post-emergence herbicides on growth, yield attributes, weed index, herbicide-efficiency index and phytotoxicity of rainy season grain sorghum (pooled data: 2019 and 2020)

Treatment	Plant height (cm)	Panicles /m^2	100-seed weight (g)	Grains/ panicle	Grain yield (t/ha)	Stover yield (t/ha)	Weed index	Herbicide efficiency index	Phytotoxicity (0–10 scale)
Atrazine @ 0.50 kg a.i./ha (PE): T_1	190.5	16.35	3.24	3329	3.04	11.58	11.71	1.99	0.33
T_1 + atrazine as PoE at 20 DAS	193.5	15.93	3.32	3370	2.92	10.74	15.38	2.07	0.67
T_1 + topramezone @ 0.0126 kg a.i./ha (PoE, 25 DAS)	190.7	11.52	3.13	2549	1.85	7.50	46.15	1.71	2.83
T_1 + tembotrione @ 0.0242 kg a.i./ha (PoE, 25 DAS)	187.2	9.47	3.14	2190	1.45	7.17	55.95	1.98	3.83
T_1 + topramezone @ 0.0189 kg a.i./ha (PoE, 25 DAS)	188.8	9.03	2.94	1940	1.15	4.42	66.20	–0.26	4.67
T_1 + tembotrione @ 0.0363 kg a.i./ha (PoE, 25 DAS)	181.3	8.78	2.93	1807	1.22	4.66	63.42	1.04	5.17
Weed-free (hand-weeding at 15 and 35 DAS)	183.8	17.11	3.35	3581	3.47	12.34	-	4.74	0.00
Weedy check	175.8	14.12	2.70	2423	1.26	5.49	63.57	-	-
CD (P=0.05)	8.29	1.32	0.148	134.4	0.224	0.783	6.04	1.02	0.66
2019	190.0	16.85	3.13	2600	2.15	9.63	45.31	0.54	2.50
2020	182.9	8.73	3.06	2697	1.94	6.35	35.29	2.77	1.88
CD (P=0.05)	4.14	0.661	0.074	67.2	0.112	0.392	3.02	0.51	0.329

DAS, Days after sowing; PE, pre-emergence; PoE, post-emergence the grain and stover yields by 64 and 55%, respectively, as compared to weed-free treatment (3.47 and 12.34 t/ha). Atrazine (PE) application has bridged the above grain and stover yield gap between weedy check and weed-free treatment by 80.4 and 89.0%. The magnitude of sorghum grain yield reductions due to weed stress and its offsetting with atrazine (PE) application reported in this study were close to those reported (50.9 and 78.8%) by Jat *et al.,* (2012) for the same location of study. Atrazine (PoE) over its PE failed to boost the productivity and on the contrary lowered the grain and stover yields by 3.95 and 7.25% on account of slight phytotoxicity (0.67). Phytotoxicity of atrazine to sorghum, as measured by stunted growth (Grichar *et al.,* 2005) and reduced grain yields (Le Court de Billot and Nel, 1985) as a result of early post-emergence treatment and sustained exposure, has been documented in previous research, which supports the current findings. Both the HPPD enzyme inhibitive PoE herbicides, i.e. tembotrione (0.0189 kg a.i./ha) and topramezone (0.0242 and 0.0363 kg a.i./ha) proved ineffective as evident from their at par grain yields as weedy check (1.26 t/ha). However, stover yields recorded with tembotrione and topramezone at their higher dose (0.0363 and 0.189 kg a.i./ha) were markedly lower (15.1 and 19.6% lesser) to weedy check (5.49 t/ha). The reduction in stover yields could be attributed to the plants' inability to generate panicles rather than the shorter plant heights. In comparison to atrazine-PE (3.04 t/ha), both topramezone and tembotrione as PoE following atrazine (PE) reduced the sorghum grain yields by 39.1 and 62.2% at low dose and 52.3 and 59.9% at high dose respectively. Reductions in stover yields were almost of similar magnitude as that of grain yield. On account of taller plants and higher yield attributes, weed-free treatment recorded the highest grain and stover yields while the least by the weedy check. Grain yields in the other herbicidal treatments were moderated as a product of yield attributes when compared to weed-free and weedy check treatments.

Weed index and Herbicide efficiency index

Weed index (WI), a measure of yield reduction from weed-free treatment, were the least (11.71) and the highest (66.20) with atrazine (PE) + topramezone (0.0189 kg a.i./ha, PoE) and the latter's WI was at par with that of weedy check (63.57). On the contrary, HEI, a measure of yields over weedy check, were highest in weed-free treatment (4.74) and decreased with the use of PoE herbicides. Topramezone (0.0189 kg a.i/ha) showed the least (–0.26) HEI value. The high WI and low (even negative) HEI values with topramezone and tembotrione herbicides compared to atrazine (PE) proves the phytotoxicity effects to grain sorghum crop (Table 3).

Economics

Economics data computed (Table 4) revealed that, weed-free (hand-weeding at 15 and 35 DAS) treatment costing ₹8,000 enhanced the cost of grain sorghum crop production by 31.3% over weedy check (₹25,565) and revealed the markedly higher net income than all the other weed-management treatments (₹135,126). Atrazine (PE), though costed only 11.4% of weed-free treatment. However, on account of its 12.4 and 6.2% lower grain and stover yields significantly lowered the net returns (6.7%) compared with weed-free treatment. From benefit: cost (B : C) ratio point of view, atrazine (PE) was superior to weed free treatment (5.76 vs. 5.03). Higher B : C ratio of atrazine (PE) was ascribed to its 21.1% lower cost of production than weed-free treatment. Topramezone (0.0189 kg a.i./ha) and tembotrione (0.0363 kg a.i./ha) as PoE compared to atrazine (PE) resulted in 35.4 and 28.6% lower net returns than weed free treatment (₹41,875). Over atrazine (PE),

Table 4. Economics of rainy season grain sorghum cultivation under different weed-management practices (pooled data)

Treatment	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	Benefit: cost ratio
Atrazine @ 0.50 kg a.i./ha (PE): T_1	26,475	152,535	126,060	5.76
T_1 + atrazine as PoE at 20 DAS	27,385	144,157	116,772	5.26
T_1 + topramezone @ 0.0126 kg a.i./ha (PoE, 25 DAS)	30,678	95,416	64,738	3.12
T_1 + tembotrione @ 0.0242 kg a.i./ha (PoE, 25 DAS)	31,118	82,791	51,673	2.67
T_1 + topramezone @ 0.0189 kg a.i./ha (PoE, 25 DAS)	30,903	57,937	27,034	1.87
T_1 + tembotrione @ 0.0363 kg a.i./ha (PoE, 25 DAS)	31,503	61,406	29,903	1.94
Weed-free (hand-weeding at 15 and 35 DAS)	33,565	168,691	135,126	5.03
Weedy check	25,565	67,440	41,875	2.64
CD (P=0.05)	–	–	6882	0.227
2019	29,649	116,935	87,286	3.99
2020	29,649	90,658	61,009	3.08
CD (P=0.05)	–	–	3,441	0.114

DAS, Days after sowing; PE, pre-emergence; PoE, post-emergence topramezone (0.0126 and 0.0189 kg a.i./ha) and tembotrione (0.024 and 0.0363 kg a.i./ha) have resulted in 51.4 and 21.4 and 41.0 and 23.7% loss in net revenues. Net income and B : C ratio of 2019 were 43.1 and 29.6% higher than 2020 (₹61,009 and 3.08) on account of 10.8 and 51.7% higher grain and stover yields.

It is concluded from the 2 years study that, pre-emergence atrazine @ 0.5 kg a.i./ha was the best herbicide weed-management option for rainy season grain sorghum of Rajasthan though weed-free situation created through 2 hand-weedings at 15 and 35 days after sowing proved the best. The HPPD (p-hydroxy-phenyl-pyruvate dioxygenase) enzyme-inhibitive post-emergence herbicides (topramezone and tembotrione) though highly effective for weed management but on account of their phytotoxicity proved to be of no practical utility at the doses tested.

REFERENCES

Dalley, C., Bernards, M. and Kells, J. 2006. Effect of weed removal timing and row spacing on soil moisture in corn (*Zea mays*). *Weed Technology* **20**(2): 399–409.

Dan, H.A., Barroso, A.L.L., Dan, L.G.M., Procópio, S.O., Ferreira Filho, W.C. and Menezes, C.C.E. 2010. Tolerância do sorgo granífero ao herbicida tembotrione. *Planta Daninha* **28**: 615–620.

DoES. 2019. *Agricultural Statistics at Glance*. Normal Estimates (Average of 2013–14 to 2017–18) of Area, Production and Yield of Major Crops in India. Ministry of Agriculture and Farmers Welfare Department of Agriculture, Cooperation and Farmers Welfare, Directorate of Economics and Statistics. pp. 44.

Gharde, Y., Singh, P.K., Dubey, R.P. and Gupta, P.K. 2018. Assessment of yield and economic losses in agriculture due to weeds in India. *Crop Protection* **107***:* 12–18.

Gill, H.S. and Vijayakumar. 1969. Weed index–a new method for reporting weed control trial. *Indian Journal of Agronomy***14**(1): 96–98.

Gomez, K.A. and Gomez, A.A. 1984. *Statistical Procedures for Agricultural Research*, edn 2. Wiley Inter-Science Publication, John Wiley & Sons, New York, USA.

Grichar, W.J., Besler, B.A. and Brewer, K.D. 2005. Weed control and grain sorghum *(Sorghum bicolor)* response to post-emergence applications of atrazine, pendimethalin and trifluralin. *Weed Technology* **19** (4): 999–1,003.

Heap, I. 2020. The international survey of herbicide resistant weeds. Available Online at: http://www.weedscience.org.

Jat, A.L., Massey, J.X., Singh, Pushpendra and Sumeriya, H.K. 2012. Response of sorghum [*Sorghum bicolor* (L.) Moench] cultivars to weed management. *Crop Research* **44**: 292–294.

Kohrt, J.R. and Sprague, C.L. 2017. Response of a multiple resistant Palmer amaranth (*Amaranthus palmeri*) population to four HPPD-inhibiting applied alone and with atrazine. *Weed Science* **65**(4): 1–12.

Le Court de Billot, M.R. and P.C. Nel. 1985. Recovery of grain sorghum [*Sorghum bicolor* (L.) Moench] from atrazine and cyanazine phytotoxicity. *South African Journal of Plant and Soil* **2**(3): 146–150.

Mishra, J.S. and Talwar, H.S. 2020. Weed management in sorghum. (In) *Sorghum in the 21st Century: Food–Fodder–Feed–Fuel for a Rapidly Changing World*. (Tonapi, V.A., Talwar, H.S., Ashok Kumar, A., Venkatesh Bhat, B., Ravinder Reddy, Ch. and Dalton, T.J. (Eds), pp. 639–664. Springer, Singapore.

Mishra, J.S., Rao, S.S. and Patil, J.V. 2014. Influence of sorghum cultivars and weed management practices on nutrient uptake by crop and weeds in semi-arid tropical India. *Indian Journal of Plant Physiology* **19**(4): 351–355.

Murty, M.V.R., Piara Singh, Wani, S.P., Khairwal, I.S. and Srinivas, K. 2007. Yield Gap Analysis of Sorghum and Pearl Millet in India Using Simulation Modeling. Global Theme on Agroecosystems Report no. 37. International Crops Research Institute for the Semi-Arid Tropics. Patancheru, Andhra Pradesh, India, pp. 82.

Sharma, A.R., Toor, Amardeep Sur and Hardip. 2000. Effect of interculture operations and scheduling of atrazine application on weed control and productivity of rainfed maize (*Zea mays*) in Shiwalik foothills of Punjab. *Indian Journal of Agricultural Sciences* **70**(11): 757–761.

Singh, V.P., Guru, S.K., Kumar, A., Banga, A. and Tripathi, N. 2012. Bioefficacy of tembotrione against mixed weed complex in maize. *Indian Journal of Weed Science* **44**(1): 1–5.

Takano, H.K., Rubin, R.D.S., Marques, L.H., Tronquini, S.E.M., Fadin, D.A., Kalsing, A., Neves, R. and Junior, O.E.P. 2016. Potential use of herbicides indifferent sorghum hybrids. *African Journal of Agricultural Research* **11**(26): 2,277–2,285.

Walia, U.S., Singh, S. and Singh, B. 2007. Integrated control of hardy weeds in maize. *Indian Journal of Weed Science* **39**: 17–20.