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EVALUATING SUITABLE CHEMICAL OPTIONS TO MANAGE *Parthenium hysterophorus* L. IN AUTUMN PLANTED MAIZE

Muhammad Ehsan Safdar[1,*], Asif Tanveer[2], Muhammad Ather Nadeem[1], Sajad Hussain[4], Nasir Iqbal[5], Muhammad Mansoor Javaid[1], Hafiz Haider Ali[1], Rashad Mukhtar Balal[3] and Muhammad Yasin[1]

[1]Department of Agronomy, College of Agriculture, University of Sargodha, Sargodha, Pakistan; [2]Department of Agronomy, University of Agriculture Faisalabad, Faisalabad, Pakistan; [3]Department of Horticulture, College of Agriculture, University of Sargodha, Sargodha, Pakistan; [4]College of Agronomy, Sichuan Agricultural University, Chengdu, China; [5]School of Agriculture, food and wine, University of Adelaide, Australia
***Corresponding author's email: ehsan_safdar2002@yahoo.com**

Parthenium hysterophorus L. (parthenium weed) is a destructive invasive weed in agroecosystems of >45 countries. Chemical control is highly effective and economical against parthenium among various weed control strategies. This two-year field study was carried out to evaluate the effectiveness of five herbicides applied 25 days after parthenium emergence viz., atrazine 80WDG at 360 g a.i. ha^{-1}, atrazine + S-metolachlor 720SC (320:400) at 720 g a.i. ha^{-1}, bromoxynil + MCPA + metribuzin 720EW (20:20:7) at 470 g a.i. ha^{-1}, atrazine + nicosulfuron 22SC (2.5:19.5) at 385 g a.i. ha^{-1} and dicamba 40.6AS at 304.5 g a.i. ha^{-1}. Application of bromoxynil + MCPA + metribuzin provided 100% control. Dicamba was the second most effective herbicide with the lowest parthenium dry weight (2.9 to 9.7 g m^{-2}) and its uptake of N (1.5 to 4.5 kg ha^{-1}), P (0.16 to 0.66 kg ha^{-1}) and K (1.0 to 3.9 kg ha^{-1}). Herbicide applications increased maize grain yield by 23 to 138%. Bromoxynil + MCPA + metribuzin at 470 g a.i. ha^{-1} showed superlative performance by achieving the highest grain yield (9.51 t ha^{-1}). This herbicidal mixture was proved to be the most efficient and economical for parthenium control as it exhibited the highest marginal rate of return (706 to 750%). It is recommended that Bromoxynil + MCPA + metribuzin at 470 g a.i. ha^{-1} should be used for controlling parthenium in maize crop.
Keywords: Bromoxynil, dicamba, grain yield; herbicides; marginal rate of return.

INTRODUCTION

Parthenium (*Parthenium hysterophorus* L.) is an invasive weed posing severe challenges and economic losses to agroecosystems in >45 countries (Adkins *et al.*, 2019) belonging to Africa (McConnachie *et al.*, 2011), Asia (Shabbir and Bajwa, 2006), Australia and Latin America (Adkins and Shabbir, 2014). It destructs biodiversity of natural communities, causes losses to crops and pastures yield, and creates health hazards to humans and animals in many countries across the globe (Adkins and Shabbir, 2014). Parthenium is one of the dominant invasive weeds in Pakistan, especially in the Central Punjab (Shabbir *et al.*, 2012) and Khyber Pakhtunkhwa provinces (Khan *et al.*, 2012). Although this species was previously perceived to be a wasteland weed in Pakistan; however, now it has become a problematic botanical weed of maize, rice, cotton, sugarcane, peanut, vegetables and forage sorghum (Hashim and Marwat, 2002; Shabbir and Adkins, 2012, Bajwa *et al.*, 2019a,b; Asif *et al.*, 2019). It is considered as a major weed of maize in India, the neighboring country of Pakistan (Sharma and Gautam, 2003). Recently, in addition to native weed flora, several invasive weeds (such as *Alternanthera philoxeroides*) including parthenium has also become problematic weeds of maize (Safdar *et al.*, 2015; Nadeem *et al.*, 2019). Yield losses due to parthenium interference are up to 53% in maize (Safdar *et al.*, 2015 and 2016). The heavy infestation of this weed and huge grain yield losses in maize cropping systems in the country have necessitated the framing of appropriate management strategies to minimize the infestation of this weed.

Among various weed control strategies, herbicides are more effective and economical in crops (Yasin *et al.*, 2010; Cheema *et al*., 2020). Various non-selective herbicides e.g., glyphosate, glufosinate ammonium and paraquat are effective for controlling parthenium weed in variable situations (Mishra and Bhan, 1996; Vila-Aiub *et al.*, 2008). Parthenium weed has evolved resistance against glyphosate, 5-enolpyruvylshikimate-3-phosphate synthase (EPSP), glutamine synthetase (GS), acetolactate synthase (ALS) and synthetic auxin in fruit orchards (Vila-Aiub *et al.*, 2008; Mora *et al.*, 2019; Palma-Bautista *et al.*, 2020). Therefore, ensuring herbicide diversity for chemical weed control is a pre-requisite rather than solely relying on few herbicides to manage such a noxious weed (Norsworthy *et al.*, 2012; Evans *et al.*, 2015). Previous studies indicated the efficient control of parthenium weed in maize, rice and forage sorghum by herbicides atrazine, prometryn, pendimethalin, S-metolachlor; bispyribac-sodium plus bensulfuron-methyl; and dicamba resulting in 71%, 37% and 25% improvement in crop yields (Khan *et al.,* 2014, Bajwa *et al.,* 2019b; Asif *et al.,* 2019; Shahnawaz *et al*., 2019). Atrazine, metribuzin and bromoxynil are photosynthetic inhibitors belonging to triazine, triazinone and nitrile herbicide groups, respectively (Retzinger and Mallory-Smith, 1997). These herbicides have been extensively used to control broadleaf weeds in maize (Gast, 1970). These are being used in mixture with other herbicides such as nicosulfuron (amino acid inhibitor) and metolachlor (cell division inhibitor). Similarly, dicamba is an auxinic group herbicide with growth regulator type mode of action and is popular among farmers due to its instant phytotoxic action and better efficacy against broadleaf weeds including parthenium in cereals (Chang and Born, 1971, Asif *et al.*, 2019). There is a lack of knowledge regarding effectiveness of maize herbicides available in Pakistan against parthenium weed. Keeping in view the effectiveness of atrazine, S-metolachlor, nicosulfuron, bromoxynil, MCPA, metribuzin and dicamba against broadleaf weeds in maize crop, their various combinations as formulated products available in market were tested against parthenium weed. The objective was to identify suitable chemical control options against this weed in autumn maize. The outcomes of the present study would provide the choice to maize growers the better and cost-effective chemical control of parthenium weed.

MATERIALS AND METHODS

Field studies were performed for two consecutive autumn planting seasons (year 2012 and 2013) at the Department of Agronomy Research Farm of University of Agriculture, Faisalabad, Pakistan. The study site was located at 31.25 ^{o}N latitude, 73.09 ^{o}E longitude and 184.4 m altitude. The experimental soil was moderately coarse textured belonged to Lyallpur soil series with 7.8 pH and 0.65% organic matter. The prevailing monthly mean temperatures were 17-33^{o}C and 19-33^{o}C during growing seasons of 2012 and 2013, respectively. The total rainfalls received during experimental periods (July-November) of 2012 and 2013 were 259 and 123 mm, respectively.

The treatments were arranged as per randomized complete block design. Each treatment had four replications with a net plot size of 7.5 m × 2.8 m. Land preparation during both years was accomplished by carrying out three cultivations followed by planking to obtain fine seedbed. During both the years of study, Nitrogen (N) at the rate of 200 kg ha^{-1} and P_2O_5 at the rate of 115 kg ha^{-1} were applied through urea and diammonium phosphate fertilizer sources, respectively. Half dose of N and full dose of P_2O_5 were broadcasted over soil just before preparation of final seedbed, whereas remaining N was top-dressed to maize crop at knee height (six leaf growth stage). Maize hybrid DK-919 obtained from Monsanto Pakistan (Pvt) Ltd. was sown on July 25, 2012 and August 3, 2013 with the help of dibbler by dropping single seed per hole while maintaining a plant-to-plant distance of 20 cm. Seed rate used was 20 kg ha^{-1}, while row to row distance was kept at 70 cm. Just after sowing, parthenium seed (having 100% germination) harvested from fully mature parthenium plants was manually broadcasted throughout the field uniformly at 15 kg ha^{-1} rate to assure adequate weed stand. Parthenium density of 20 plants m^{-2} was found to be uniform throughout the experiment by random sampling carried out 25 days after parthenium emergence. Five herbicides namely, atrazine (Clark Plus 80WDG) at 360 g a.i. ha^{-1}, atrazine + S-metolachlor [Primextra Gold 720SC (320:400)] at 720 g a.i. ha^{-1}, atrazine + nicosulfuron [Synergy 22SC (2.5:19.5)] at 385 g a.i. ha^{-1}, bromoxynil + MCPA + metribuzin [Valent 470EW (20:20:7)] at 470 g a.i. ha^{-1} and dicamba (Commit 40.6AS) at 304.5 g a.i. ha^{-1} 35 days after sowing were used in the experiment. In addition, no weed control was regarded as weedy check. Post-emergence spray of herbicides was carried out 25 days after parthenium emergence (at rosette stage) with knapsack sprayer (Solo Model 425) fitted with a flat fan nozzle. Before the spray, sprayer calibration was done to 250 L per ha water. All other weeds that emerged over the growing season were removed by hand pulling soon after their emergence.

In both the years, manual crop harvesting was done at the harvest maturity (in last week of November). Parthenium density and dry biomass per m^2, and N, phosphorus (P) and potash (K) uptake per ha were noted at crop harvest. The dry weight of parthenium was obtained by drying above ground harvested parthenium plants at 70 ^{o}C for 48 hours in an electric drying oven (Memmert, Germany). The ground plant material of dried parthenium weed samples was used for determining their NPK contents according to procedure of Williams (1984). The parthenium NPK contents after multiplying with their respective dry biomasses were converted into NPK uptakes. The maize grain yield and underlying traits (grain count cob^{-1}, weight of grains cob^{-1}, 100 grain weight and harvest index) were observed from plants harvested from whole plot after drying grain to 15% moisture. Grain count cob^{-1} was calculated from the total number of grains of ten randomly selected cobs from each plot. Weight of grains cob^{-1} was calculated from the total weight of grains of ten randomly selected cobs from each plot. For 100 grain weight (g), three samples of 100 grains were taken randomly from seed lot of each plot, weighed and then averaged. Harvest index (%) was calculated by using the given below formula of Beadle (1987) as:

$$Harvest\ index = \frac{Grain\ yield}{Biological\ yield} \times 100 \text{ (Equation 1)}$$

The herbicidal weed control efficiencies (WCE) were computed according to the equation described by Kondap and Upadhyay (1992):

$$WCE = \frac{W1-W2}{W1} \times 100 \quad \text{(Equation 2)}$$

Where, W_1 = weed dry biomass in control treatment, and W_2 = weed dry biomass in herbicide treatment

Herbicide efficiency index (HEI) was determined by the equation described by Walia (2003):

$$HEI = \frac{YT - YC}{YC} \times 100 \Big/ \frac{DMT}{DMC} \times 100 \quad \text{(Equation 3)}$$

Where, YT = grain yield of the herbicide treated plot, YC = grain yield of the control plot, DMT = weed dry biomass in herbicide treated plot and DMC = weed dry biomass in control plot.

Maize grain N content was determined by micro-Kjeldhal distillation technique (Anonymous, 1980). To calculate grain protein content, following formula as suggested by Salo-väänänen and Koivistoinen (1996) was used:

$$\%\text{protein} = \%\text{N} \times 6.25 \quad \text{(Equation 3)}$$

Two-year data were statistically analyzed by Fischer's analysis of variance procedure by combined over year option on MSTATC statistical package (Fischer, 1990). Means' comparison was done using the least significant difference test at 5% probability (Steel *et al.,* 1997). The parameters for which year effect was not significant, were pooled to get the mean of years. Regression analyses were carried out through MS Excel program. By single degree of freedom, contrast analysis was carried out for different herbicide treatments (Little and Hills, 1978). The treatments' economic analysis was worked-out keeping in view the prevalent herbicides and crop produce market prices. The method suggested by CIMMYT (1988) was used to calculate marginal rate of return (MRR) as ratio of marginal net benefit and marginal cost.

RESULTS

Parthenium growth characteristics: *Parthenium density and dry biomass per m^2*. Density and biomass of parthenium were significantly influenced by all herbicides (Table 1). All herbicides reduced the density and biomass compared with weedy check treatment. No parthenium plant was observed at harvest in bromoxynil + MCPA + metribuzin treated plots during both study years. The lowest parthenium density (3.5 and 3.2 plants m^{-2} during 2012 and 2013, respectively) was observed in response to dicamba which was statistically similar to that recorded with atrazine + S-metolachlor and atrazine + nicosulfuron during 2012. However, parthenium density was not significantly altered by applied herbicides during 2013. Dicamba also resulted in the lowest parthenium dry biomass (9.7 and 9.3 g m^{-2}, respectively) during both years of study. The atrazine herbicide resulted in the lowest biomass reduction in both years.

Contrast comparison indicated the significant difference of weedy check from herbicide showing that all herbicides significantly declined weed density compared with control. It also showed significant difference between atrazine alone and atrazine along with other combinations (Table 1). However, all contrasts regarding parthenium dry weight remained significant for both years.

Table 1. Parthenium density and its dry biomass in maize as influenced by herbicide application.

Herbicides	Density (plants m^2)		Dry biomass (g m^{-2})	
	2012	**2013**	**2012**	**2013**
Weedy check	48.5a	39.5a	96.0a	90.2a
Atrazine	19.0b	15.7b	56.5b	47.6b
Atrazine + nicosulfuron	8.2c	5.7bc	38.6c	26.9c
Atrazine + S-metolachlor	5.0c	2.7bc	21.6d	12.4d
Bromoxynil+MCPA+metribuzin	0.0c	0.0c	0.0f	0.0e
Dicamba	3.5c	3.2bc	9.7e	9.3e
LSD ≤ 0.05	9.94	15.16	7.84	8.25
Year means	14.0A	10.8B	37.1A	30.0B
LSD (year)	2.83		4.87	
Contrasts				
Weedy check vs all	**	**	**	**
Atrazine single vs atrazine combinations	**	**	**	**
Herbicide mixtures vs single herbicide	NS	NS	**	**

Mean values in a column with dissimilar lettering vary significantly ($P < 0.05$) from one another as per least significant difference (LSD) test, Year means showing different capital letters significantly differ at 0.05 probability level, ** = significant at 0.01 probability, NS = Non-significant

Weed control efficiency (WCE) and herbicide efficiency index (HEI). Maximum WCE (100%) was shown by bromoxynil + MCPA + metribuzin during both years of study (Fig.1). However, atrazine performed the worst by giving 41 and 43% WCE during the 2012 and 2013, respectively. Among all the tested herbicides, bromoxynil + MCPA + metribuzin recorded the highest HEI (100) in both years. However, atrazine recorded the lowest (7.0 and 7.3) values of HEI during 2012 and 2013, respectively.

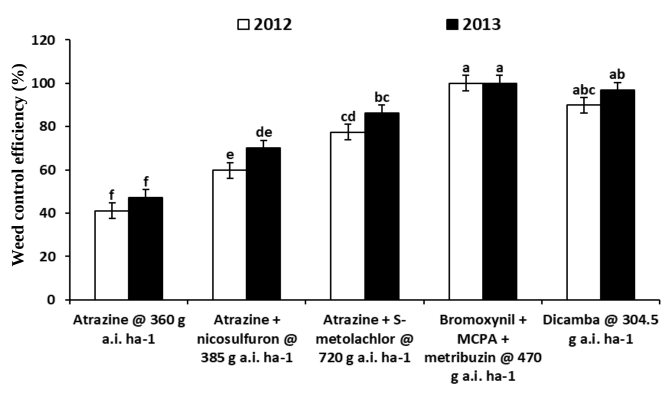


Figure 1. Comparison of herbicidal WCE. Bars with dissimilar lettering vary significantly from one another at 0.05 probability. Error bars represent standard errors

Table 2. Nutrient uptake (kgha^{-1}) by parthenium as influenced by herbicide application

Herbicides	Nitrogen uptake		Phosphorus uptake		Potash uptake	
	2012	**2013**	**2012**	**2013**	**2012**	**2013**
Weedy check	27.3a	41.9a	4.07a	2.25a	24.3a	25.0a
Atrazine	18.6b	22.3b	2.68b	1.33b	17.4b	14.2b
Atrazine + nicosulfuron	14.0c	13.2c	2.05c	0.86c	13.3b	8.4c
Atrazine + S-metolachlor	8.1d	6.3d	1.30d	0.57d	7.5c	4.0d
Bromoxynil+MCPA+metribuzin	0.0f	0.0e	0.00f	0.00f	0.0d	0.0e
Dicamba	4.5e	4.7de	0.66e	0.47e	3.9cd	3.1e
LSD ≤ 0.05	2.20	4.96	0.376	0.288	4.36	2.90
Year means	12.1B	14.2A	1.8A	0.9B	11.1A	8.8B
LSD (year)	1.25		0.51		1.85	
Contrasts						
Weedy check vs all	**	**	**	**	**	**
Atrazine single vs atrazine combinations	**	**	**	**	**	**
Herbicide mixtures vs single herbicide	**	**	**	**	**	**

Mean values in a column with dissimilar lettering vary significantly ($P < 0.05$) from one another as per least significant difference (LSD) test, Year means showing different capital letters differ significantly at 0.05 probability level, ** = Significance 0.01 probability

Parthenium nutrient uptake. Parthenium N, P and K uptake was decreased by the application of herbicides (Table 2). The lowest N uptake (4.5 and 4.7 kg ha^{-1}), P uptake (0.66 and 0.47 kg ha^{-1}) and K uptake (3.9 and 3.1 kg ha^{-1}) by parthenium during 2012 and 2013, respectively were noted from plots treated with dicamba. However, N uptake in 2013 and K uptake in 2012 were statistically at par with atrazine + S-metolachlor. During both the years, all contrast comparisons showed significant differences regarding NPK uptake by parthenium.

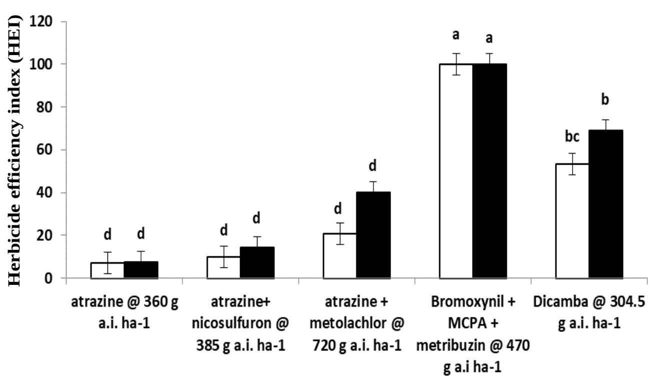


Figure 2. Comparison of HEI of herbicides. Bars with dissimilar lettering vary significantly from one another at 0.05 probability. Error bars represent standard errors

***Maize grain yield and underlying traits*:**

Grain count per cob. Data related to grain count per cob (Table 3) of maize indicated significant improvement in this parameter by all herbicides. The highest grain count per cob (511.7) was noted from maize plants harvested from bromoxynil + MCPA + metribuzin treated plots that were statistically similar to those treated with dicamba. All the contrasts regarding this parameter were statistically significant except herbicide mixtures versus single herbicides (Table 3).

100-grain weight. The 100-grain weight of maize showed significant improvement in response to herbicides in comparison to control (Table 3). Among the herbicides, bromoxynil + MCPA + metribuzin treated plots had the highest 100-grain weight (33.4 g) of maize that was statistically similar to those observed in case of dicamba, atrazine + S-metolachlor and atrazine + nicosulfuron. Contrasts of control versus herbicides and atrazine combinations versus non-atrazine combinations were significant regarding this yield component (Table 3).

Weight of grains per cob. Significantly the highest weight of grains per cob (170.5 g) was observed with bromoxynil + MCPA + metribuzin. All contrast comparisons showed significance pertaining to weight of grains per cob.

Grain yield (t ha^{-1}). All herbicide treatments significantly increased the grain yield of maize over weedy check. Significantly, the highest grain yield of maize (4.90 t ha^{-1}) was obtained from plots where bromoxynil + MCPA + metribuzin was applied. The lowest grain yield (4.90 t ha^{-1}) of maize was noted in plots treated with atrazine + nicosulfuron. All contrast comparisons showed significant differences between various treatments (Table 3). A significant positive dependence of grain yield on grain count per cob ($R^2 = 0.79$), 100-grain weight ($R^2 = 0.81$) and weight of grains per cob ($R^2 = 0.88$) was shown by regression analyses (Fig. 3).

Harvest index (HI). The highest (36.2%) HI of maize was observed with atrazine whereas the lowest (30%) with weedy check. Among contrasts, all contrast comparisons were non-

Table 3. Grain yield of maize and underlying traits as influenced by herbicide application.

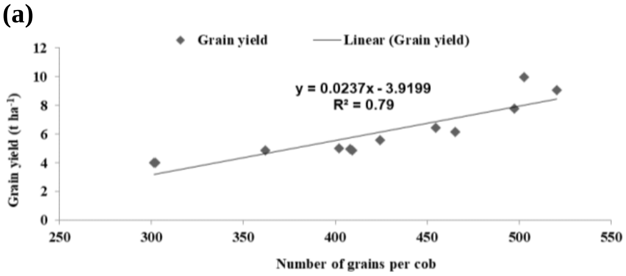
Herbicides	Grain count cob^{-1}	Weight of grains cob^{-1} (g)	100 grain weight (g)	Grain yield (t ha^{-1})	Harvest index (%)
Weedy check	301.6d	83.6e	27.9b	4.00e	30.0b
Atrazine	382.0c	109.2d	28.9b	4.93d	30.5b
Atrazine + nicosulfuron	408.8c	122.3cd	30.1ab	4.90d	31.5b
Atrazine + S-metolachlor	439.4bc	134.8bc	30.8ab	6.00c	31.4b
Bromoxynil + MCPA + metribuzin	511.7a	170.5a	33.4a	9.51a	36.2a
Dicamba	481.3ab	149.4b	31.1ab	6.96b	34.1ab
LSD ≤ 0.05	69.84	15.42	3.68	0.783	4.23
Contrasts					
Weedy check vs all	**	**	**	**	**
Atrazine single vs atrazine combinations	*	**	NS	*	**
Atrazine combinations vs non-atrazine combinations	**	**	**	**	**
Herbicide mixtures vs single herbicides	NS	**	NS	**	**

Mean values in a column with dissimilar lettering vary significantly (P < 0.05) from one another as per least significant difference (LSD) test, ** = significant at 0.01 probability, * = significant at 0.05 probability, NS = Non-significant

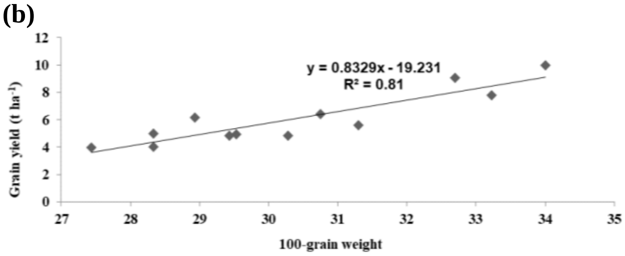
significant except weedy check versus all regarding HI of maize (Table 3).

Grain protein and oil contents of maize. The data (Fig. 4) showed that some herbicides resulted in significant improvement in protein content of maize grains. The highest protein content (10.5 and 9.0% in years 2012 and 2013, respectively) of maize grain was noted for plants harvested from plots treated with dicamba whereas the lowest (7.9%) from control.

(a)



(b)



(c)

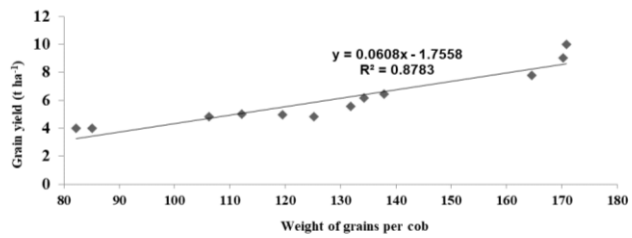


Figure 3. Relationship of grain yield of maize with (a) grain count per cob, (b) 100-grain weight and (c) weight of grains per cob under the influence of various herbicides for controlling *P. hysterophorus.*

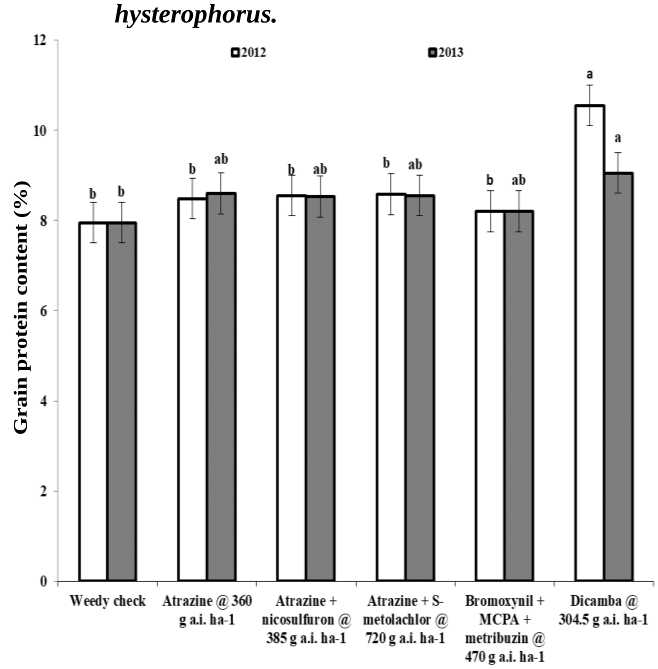


Table 4. Influence of herbicides on economic returns during year 2012 and 2013.

Herbicides	Gross income (USD ha^{-1}) (Grain + Stalk)		Cost that varied (USD ha^{-1})		Net benefits (USD ha^{-1})		Marginal net benefit (USD ha^{-1})		MRR (%)	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Weedy check	124	123	-	-	124	123	-	-	-	-
Atrazine	149	146	9	10	140	136	16	13	177	130
Atrazine + nicosulfuron	148	146	14	15	134D	131D	-	-	-	-
Atrazine + S-metolachlor	164	186	13	14	151	172	27	49	207	350
Bromoxynil + MCPA + metribuzin	253	276	16	18	237	258	113	135	706	750
Dicamba	179	220	19	21	160D	199D	-	-	-	-

Price of maize grain (Rs. = rupees): Rs.4500 / t (in year 2012) and Rs.5000 / t (in year 2013); Price of maize stalk = Rs. 3550 / ha (in year 2012) and Rs.5000 / ha (in year 2013); Price of atrazine = Rs.675 (in year 2012) and Rs.700 (in year 2013); Price of atrazine + nicosulfuron = Rs.1400 (in year 2012) and Rs.1435 (in year 2013); Price of atrazine + S-metolachlor = Rs.1275 (in year 2012)and Rs.1325 (in year 2013); Price of bromoxynil + MCPA + metribuzin = Rs.1750 (in year 2012) and Rs.2000 (in year 2013); Price of dicamba = Rs.2250 (in year 2012) and Rs.2500 (in year 2013); Labor costs of spray = Rs.750 in year 2012 and Rs.875 in year 2013 (2.5 man days ha^{-1}, Rs.300 man^{-1} in year 2012 and Rs.350 man^{-1} in year 2013); Rent of sprayer = Rs.100; MRR = Marginal rate of return; D = Dominated treatment, USD = US dollar (Rs.159 = 1 US dollar)

Figure 4. Influence of various herbicides aimed at controlling *P. hysterophorus* on grain protein of maize, Bars with dissimilar lettering vary significantly from one another at 0.05 probability.

Economic analysis. During both the years (2012 and 2013), bromoxynil + MCPA + metribuzin and atrazine gave the highest and lowest net benefit (Table 4). The two herbicides atrazine + nicosulfuron and dicamba were dominated. Among the remaining three herbicides, the maximum marginal rate of return (MRR) (706 and 750% in the year 2012 and 2013, respectively) was observed for bromoxynil + MCPA + metribuzin.

DISCUSSION

The post-emergence herbicides bromoxynil + MCPA + metribuzin and dicamba application gave the best control of parthenium weed in terms of reducing its density and dry weight. The outcomes of the present investigation are similar to the findings of Khan *et al.* (2014) who stated that bromoxynil + MCPA, metribuzin, atrazine and atrazine + S-metolachlor at their application rates of 0.8, 2, 1 and 1.5 kg a.i. ha^{-1}, respectively significant decreased the density and dry biomass of parthenium in maize. Similarly, Reddy *et al.* (2007) demonstrated that bromoxynil at 560 g a.i. ha^{-1} and atrazine at 2240 g a.i. ha^{-1} as their post-emergence applications resulted in 36% reductions in parthenium density as noted 21 days after herbicide spray. Among different herbicides applied as post-emergence, Javaid (2007) found bromoxynil + MCPA at 1.0, 0.75, 0.5 and 0.25 kg ha^{-1} to be the most effective against parthenium as it resulted in 100% mortality of 5 and 8 weeks old parthenium plants within 7 days of spraying. Rehman *et al.* (2017) found atrazine, bromoxynil and metolachlor to be the most effective in controlling parthenium weed in spring maize. Wožnica and Idziak (2010) demonstrated the weed control efficiency of nicosulfuron and tritosulfuron + dicamba herbicides applied as post-emergence in the range of 92 to 99% in maize. Both the herbicides bromoxynil + MCPA + metribuzin and dicamba giving better control of parthenium are auxin growth regulators. However, metribuzin which is photosynthetic inhibitor caused variability of phytotoxicity among these herbicides. The superiority of bromoxynil + MCPA + metribuzin over dicamba was probably due to synergistic interaction of photosynthetic inhibitor with auxin growth regulator. Studies suggested that glyphosate, chlorimuron ethyl, atrazine, bromoxynil, ametryn and metsulfuron were very effective in controlling this weed but efficacy of each herbicide was variable (Kaur *et al.,* 2014). According to herbicide screening studies by Javaid (2007) and Gaikwad *et al.* (2008), compete control of parthenium occurred by 2,4-D and metribuzin at 15 days after spraying. Another study by Khan *et al.* (2012) suggested that parthenium weed control by an herbicide depended upon the weed growth stage and time of application. They concluded that metribuzin and glyphosate had higher control of this weed than other herbicides when applied at its rosette and bolted stage 4 weeks after treatment.

The HEI is an indicator of percent crop yield increase per unit decrease in weed dry and takes into account the phytotoxic effect of an herbicide on crop along with weed suppression. The mixture of bromoxynil + MCPA + metribuzin got the higher HEI might be due to its least or no suppressive effect on maize crop along with better weed control. Our results corroborate the conclusions of Mahajan and Chauhan (2015) who suggested that tank mixture of azimsulfuron plus bispyribac plus fenoxaprop was most effective than their use alone for controlling broad leaf weeds of direct seeded rice and enhancing its yield. Moreover, Bijanzadeh and Ghadiri (2006) described that maximum corn yield was achieved with combination of atrazine and alachlor compared to that by their use alone. According to Muoni *et al.* (2013), herbicide mixtures (atrazine and metolachlor) showed better performance than their application alone due to their enhanced efficacy against invasive weed species in maize without harming the maize crop. Rehman *et al.* (2017) also pointed out that post-emergence application of herbicide mixtures atrazine + S-metolachlor and bromoxynil + MCPA attained the higher HEI for controlling parthenium weed in spring maize.

Reduction in parthenium NPK uptake by herbicides might occur due to reduction in its dry matter per unit area. Kelaginamani and Halikatti (2002), Anjum *et al.* (2007) and Sonawane *et al.* (2014) also established that weed NP uptake tended to decline significantly in response to pre-emergence and post-emergence application of atrazine and 2,4-D in maize crop. Głowacka (2011) also reported that *Galinsoga parviflora* Cav., *Cirsium arvense* L. and *Chenopodium album* L. showed a significant decrease in their K-uptake in response to herbicidal application in maize crop. The increase in grain count and grain weight of maize by herbicides was probably the result of decrease in weed competition stress during reproductive growth phase of crop. As suggested by Khan *et al.* (2014), prominent enhancement in grain count and grain weight of maize occurred when metribuzin, bromoxynil + MCPA, atrazine + S-metolachlor and atrazine herbicides were sprayed to control weeds.

In our study, all herbicides resulted in maize grain yield improvement to variable degree. However, the best performance was shown by bromoxynil + MCPA + metribuzin and dicamba on account of better parthenium control. Grain count and grain weight were proved to be the major factors that contributed towards greater maize grain yield. It is revealed by the strong positive grain yield regression relationship with these two yield components. Haji *et al.* (2012) also achieved considerably the greater maize grain yield by effective chemical control of weeds. Nadeem *et al.* (2010) and Mahadi (2014) demonstrated maize grain yield increments of up to 298% by atrazine + metolachlor and atrazine herbicides through effective weed control. Moreover, Wožnica and Idziak (2010) reported the substantial enhancement in maize grain yield in response to nicosulfuron and tritosulfuron + dicamba post-emergence application on account of up to 6 and 21% control of broadleaf weeds, respectively. Herbicide combinations metribuzin + flufenacet, bromoxynil + sulcotrione, and nicosulfuron + thifensulfuron-methyl caused up to 87% weed control in maize along with up to 19% enhancement in maize grain yield (Knežević *et al.,* 2003; Grichar *et al.,* 2003). A significant improvement in maize grain yield through enhanced grain number per cob and grain weight by effective weed control occurred by application of metribuzin (Saudy, 2013).

Improvement in HI of maize by herbicides could be the result of improved partitioning of photosynthates in grain part of the crop on account of reduced severity of weed competition stress during reproductive growth phase of crop. Khan *et al.* (2014) also concluded that maize HI was enhanced over untreated weedy check in response to atrazine application as it gave better weed control. The enhancement in grain protein content with dicamba could be ascribed to higher uptake of N by crop on account of decreased weed infestation. Outcomes of the present study corroborate the findings of Chopra and Angiras (2007) that showed slight improvement in protein content of maize grain due to reduced weed competition stress by chemical weed control. Bajwa *et al.* (2019b) concluded that pre-emergence application of pendimethalin followed by post-emergence application of bispyribac-sodium + bensulfuron-methyl gave the excellent control of parthenium weed along with improved yield and net profit in direct-seeded rice.

***Conclusions*:** It is concluded that among tested herbicides, bromoxynil + MCPA + metribuzin was proved to be better regarding parthenium suppression, maize yield improvement and cost-effectiveness. However, dicamba may also be used for better control of this weed in maize.

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