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Bioefficacy, Phytotoxicity and Economics of Post-emergence Herbicides in Moth Bean (*Vigna aconitifolia*) in Hot Arid Regions

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ABSTRACT

Background: Weed infestation is the major cause of yield loss to *Kharif* pulses in arid regions. Post-emergence herbicide application is a promising weed management option for pulses in these areas. Therefore, the current study was aimed to find an effective and economic post-emergence herbicide molecule for weed control in moth bean.

Methods: A field experiment was conducted during 2017-2019 with different herbicides, hand weeding, weed-free and unweededs in *Kharif* mung bean in a randomized complete block design with three replications.

Result: Among the herbicide treatments, post-emergence application of propaquizafop + imazethapyr @ 125 g a.i. ha^{-1} being statistically at par with clodinafop-propargyl + sodium acifluorfen @ 312.5 g a.i. ha^{-1} and hand weeding recorded the highest reduction in total weed dry matter (73.9%), highest weed control efficiency (73.8%) and lowest weed persistence index (1.03) compared to the unweeded. The reduction in seed yield in unweeded compared to weed-free and hand weeding was 50.8% and 42.1%, respectively. As the imazethapyr-containing herbicides caused crop phytotoxicity, significantly higher crop dry weight (513 g m^{-2}), seed yield (5.53 q ha^{-1}), stover yield (18.0 q ha^{-1}), gross returns and net benefits of moth bean were recorded with clodinafop-propargyl + sodium acifluorfen (312.5 g a.i. ha^{-1}) over other herbicide treatments. Clodinafop-propargyl + sodium acifluorfen (@312.5 g a.i. ha^{-1}) registered the minimum value of weed index (20) and highest values of herbicide efficiency index (3.9) and crop resistance index (4.70).

Key words: Herbicide phytotoxicity, Imazethapyr, Weed persistence, Weed interference, Weed index.

INTRODUCTION

Moth bean [*Vigna aconitifolia* (Jacq.) Marechal] is a most drought tolerant rainy season legume grown extensively in arid and semi-arid regions of India. Rajasthan, followed by Gujarat, has the highest area (98.25%) and production (97.04%) of moth bean in the country (Patel *et al.,* 2019). However, in western Rajasthan's weed infestation is the major impediment for acreage and productivity of moth bean (Jat *et al*., 2011). Depending upon the intensity and type of weed flora, weed infestation in moth bean causes a yield loss to the extent of 75% (Saxena *et al*., 2003). Hence, practical and economical weed control is the best management practice for enhancing the productivity of moth bean.

Over the years, herbicidal weed control in pulses has emerged as a promising solution. Furthermore, considering the limitations of pre-emergence herbicides (Punia *et al*., 2011), post-emergence (PoE) herbicide application provides better weed management options for farmers (Rashid *et al*., 2009). Because of its high herbicidal activity and broad-spectrum weed control, imazethapyr is emerging as a potent PoE herbicide for *Kharif* pulses (Singh *et al.,* 2016). However, other researchers also suggested higher weed control efficiency of clodinafop-propargyl + sodium-acifluorfen combination against imazethapyr in mungbean (Harithavardhini *et al*., 2016). In rainfed conditions, herbicide application generates stress even into tolerant crops and cultivars, manifesting crop phytotoxicity. Hence, before recommendation for broader use, suitable herbicide molecules should be evaluated for their phytotoxic effects and weed control efficacy in a particular agro-climatic region. Therefore, the present research was carried out to find the effectiveness of different post-emergence herbicides in moth bean under arid conditions of western Rajasthan.

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MATERIALS AND METHODS

A field experiment was conducted at ICAR-Central Arid Zone Research Institute, Jodhpur (27°18′N latitude and 73°01′E longitude) from 2017 to 2019. The experimental field was well-drained with loamy sand soil low in organic carbon (0.18%) and available nitrogen (170 kg ha^{-1}), medium in available phosphorous (16.8 kg ha^{-1}) and potassium (277 kg ha^{-1}) with slightly alkaline in reaction (pH 8.3). The region's average annual rainfall is about 365 mm, mainly received during the rainy season.

Eleven treatment combinations comprising pre-emergence and post-emergence herbicides along with hand weeding, weed-free and unweeded were applied in *Kharif* moth bean (Table 1). The experiment was laid out in randomized block design with three replications keeping the plot size 5 m × 3 m. The herbicides were sprayed with a knapsack sprayer fitted with a flat fan nozzle using a water volume of 500 l ha^{-1}.

The rainfed moth bean was sown during the first fortnight of July and harvested in the second fortnight of September. Moth bean 'CAZRI Moth-2' 12 kg ha^{-1} was planted at 30 cm row spacing with the help of a seed drill. The recommended dose of fertilizers (10 kg N + 20 kg P) was applied as basal through urea and DAP. The crop was managed uniformly throughout the growth period, except for weed control.

Observations on weed infestation were recorded after harvest of crops with a quadrate of 0.5 × 0.5 m (0.25 m^2) size placed at two randomly selected places in each plot, leaving an area of 30 cm from the plot borders. Weed density (no. m^{-2}) was recorded by categorizing the sampled weeds into grasses, broad-leaved and sedges. For recording dry matter of weeds (g m^{-2}), the categorized weeds were first air-dried for five days and then oven-dried at 65±5°C until constant dry weight (~48 hrs). Phytotoxicity of herbicides was recorded at 10days after application on a 0-10-point visual score scale as suggested by Rao (2000).

The crop dry weight was recorded from five randomly selected plants from each plot just before harvesting. Seed yield and stover yield (kg ha^{-1}) were recorded based on the yield obtained from the net plot (2 m × 3 m). Economics was computed based on prevailing market prices of products and inputs. Weed control efficiency (WCE) and weed index (WI) were calculated by using the standard formula suggested by Mani *et al*. (1973). Impact indices, *viz*. weed persistence index (WPI), crop resistance index (CRI) and herbicide efficiency index (HEI), were worked out as per Sen *et al*. (2020).

The collected data for weed and crop parameters were statistically analyzed separately using SPSS (version 16.0). Before statistical analysis, the weed density and dry weed weight data were subjected to square root transformation [$(x+0.5)^{1/2}$]. Data analysis was done through analysis of variance using the F-test. Means were separated at a 5% level of significance as per Tukey's honest significant difference test.

RESULTS AND DISCUSSION

Weed interference

In terms of weed flora composition, grassy weeds were dominant, constituting about 39.6-65.3% of total weed density across the treatments, followed by broad-leaved weeds (26.3-46.6%) and sedges (6.3-28.2%). However, in terms of total weed dry matter, across the treatments dominating group was broad-leaved weeds (56.7-71.3%), followed by grassy weeds (20.7-35.4%) and sedges (4.4-13.6%) (Table 2).

Weed density and dry matter at harvest differed significantly among the weed management practices (Table 2). Among the herbicide treatments, propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_5), being at par with other imazethapyr treatments (T_2, T_3 and T_4) and hand weeding (T_9), recorded significantly lower total weed density (21.3 m^{-2}). The lowest per cent reduction in total weed dry matter compared to unweeded was recorded under clodinafop-propargyl + sodium acifluorfen @ 187.5 g a.i. ha^{-1} (T_6) (41.6%). The imidazolinones herbicides (imazethapyr and imazamox) are absorbed both by the roots and the shoots (Saltoni *et al*., 2004); hence, imazethapyr in combination with propaquizafop provided wide spectrum weed control and resulted in lesser weed counts and produced lower weed dry matter. These findings are in line with Khairnar *et al. (*2014).

Application of clodinafop-propargyl + sodium acifluorfen both at 250 g a.i. ha^{-1} (T_7) and 312.5 g a.i. ha^{-1} (T_8) also led to weed dry matter suppression at par to imazethapyr treatments (T_2, T_3, T_4 and T_5) and hand weeding (T_9). Minimum weed density and weed dry matter under propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_5) are presumably due to effective control of grassy and broadleaf weeds, especially at the early growth stages. Further, clodinafop-propargyl + sodium acifluorfen @ 312.5 g a.i. ha^{-1} (T_8)

Table 1: Weed control treatments, rate and time of application in moth bean.

Treatment	Weed management practice	Rate of application (a.i. ha^{-1})	Time of application
T_1	Pendimethalin	750 g	1 DAS
T_2	Imazethypr	50 g	20 DAS
T_3	Imazethapyr + imazamox (Pre-mix)	60 g (35 g+25 g)	20 DAS
T_4	Propaquizafop + imazethapyr (Pre-mix)	100 g (40 g+60 g)	20 DAS
T_5	Propaquizafop + imazethapyr	125 g (50 g+75 g)	20 DAS
T_6	Clodinafop-propargyl + sodium acifluorfen (Pre-mix)	187.5 g (61.9 g+125.6 g)	20 DAS
T_7	Clodinafop-propargyl + sodium acifluorfen	250 g (82.5 g+167.5 g)	20 DAS
T_8	Clodinafop-propargyl + sodium acifluorfen[#]	312.5 g (103.1 g+109.5 g)	20 DAS
T_9	Hand weeding (Farmers' practice)	Once	25 DAS
T_{10}	Unweeded	-	
T_{11}	Weed-free check (hand weeding)	Thrice	-

DAS= Days after sowing, a.i.= Active ingredient; [#]Applied during 2018 and 2019 only.

also caused effective weed control and led to 66.3% and 73.3% reductions in total weed density and total weed dry matter over unweeded (T_{10}). A narrow-spectrum activity against weeds (Table 2) rendered clodinafop-propargyl + sodium acifluorfen less effective at lower doses (T_6 and T_7). However, clodinafop-propargyl + sodium acifluorfen (@ 312.5 g a.i. ha^{-1}) (T_8) could cause sufficient growth suppression and found at par with imazethapyr treatments in weed dry matter reduction. Harithavardhini *et al.* (2016) reported higher efficacy of clodinafop-propargyl + sodium acifluorfen over imazethapyr in mung bean.

Crop phytotoxicity

The phytotoxicity rating of applied herbicides on crop growth revealed that PoE application of imazethapyr-containing herbicides (T_2, T_2, T_4 and T_5) caused a phytotoxic effect (score 1-2) on moth bean. The phytotoxic effect of herbicides caused stunting and discolouration of leaves which persisted up to flowering and reflected on the final yield of the crop as well (Table 3). Similar results of imazethapyr phytotoxicity were reported earlier by Punia *et al.* (2015) on mung bean.

Crop growth and yield

The favourable growth environment in weed-free (T_{11}) treatment resulted in the significantly highest crop dry weight (613 g m^{-2}), seed yield (6.92 q ha^{-1}) and stover yield (23.9 q ha^{-1}) over other treatments (Table 3). On the other hand, the reduction in seed yield in unweeded compared to weed-free and hand weeding was 50.8% and 42.1%, respectively. These results are in agreement with as reported by Upadhayay *et al.* (2013). Moreover, clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8) being at par with propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_5) and hand weeding (T_9) recorded significantly higher crop

Table 2: Density and dry matter of different categories of weeds in moth bean at harvest under different weed management practices (mean of three-year data)[a].

Treatment	Weed density (Nos. m^{-2})				Weed dry matter (g m^{-2})			
	Grassy	Broad-leaved	Sedges	Total	Grassy	Broad-leaved	Sedges	Total
T_1	4.9^{de} (23.7)	3.7^{cd} (13.3)	2.5^{cde} (6.0)	6.6^{de} (43.0)	5.3^{cd} (28.1)	9.8^{cd} (97)	3.4^{d} (11.3)	11.7^{d} (136)
T_2	3.9^{bc} (15.0)	3.3^{bcd} (10.3)	1.5^{b} (2.0)	5.3^{bc} (27.3)	4.4^{bc} (19.0)	6.5^{b} (45)	2.1^{b} (3.8)	8.1^{bc} (68)
T_3	3.7^{bc} (13.0)	3.8^{cd} (14.3)	1.9^{bc} (3.3)	5.6^{bc} (30.7)	4.1^{b} (16.7)	7.2^{b} (52)	3.0^{cd} (8.7)	8.8^{bc} (77)
T_4	3.4^{b} (11.3)	3.0^{bc} (8.3)	2.8^{de} (7.7)	5.3^{bc} (27.3)	4.3^{bc} (18.3)	6.8^{b} (46)	2.2^{b} (4.2)	8.3^{bc} (68)
T_5	3.5^{b} (11.7)	2.5^{b} (6.0)	2.0^{bcd} (3.7)	4.7^{b} (21.3)	4.1^{b} (16.0)	6.4^{b} (40)	2.4^{bc} (5.2)	7.9^{b} (62)
T_6	5.6^{e} (31.0)	4.2^{cde} (17.3)	3.1^{e} (9.7)	7.6^{f} (58.0)	5.9^{d} (34.8)	9.8^{cd} (98)	2.7^{bcd} (6.7)	11.8^{d} (139)
T_7	5.2^{de} (27.0)	4.3^{de} (17.7)	1.8^{bc} (3.0)	6.9^{ef} (47.7)	5.0^{bcd} (25.4)	8.1^{bc} (67)	2.2^{b} (4.3)	9.8^{bc} (97)
T_8	4.4^{cd} (19.0)	3.5^{bcd} (11.7)	1.6^{b} (2.3)	5.8^{cd} (33.0)	4.4^{bc} (19.3)	7.5^{b} (56)	2.1^{b} (4.0)	8.9^{bc} (79)
T_9	3.3^{b} (10.7)	3.5^{bcd} (12.3)	2.1^{bcd} (4.0)	5.2^{bc} (27.0)	4.1^{b} (16.3)	6.4^{b} (40)	3.1^{cd} (9.0)	8.1^{bc} (66)
T_{10}	8.2^{f} (67.7)	5.1^{e} (27.3)	3.0^{e} (8.7)	10.2^{g} (103.7)	9.2^{e} (84.3)	11.5^{d} (135)	4.3^{e} (18.5)	15.4^{e} (238)
T_{11}	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)	0.7^{a} (0.0)

Treatment details are described in Table 1; Values in parentheses are the means of original values; Means (the square root transformed ($\sqrt{X+0.5}$) values) superscripted with different letters are significant at p<0.05 as per Tukey's HSD test. [a]Values against T_8 are the mean of two-year data.

Table 3: Crop phytotoxicity, growth and yield of moth bean as influenced by different weed management practices (mean of three-year data)[a].

Treatment	Crop phytotoxicity visual rating score (10 DAT)		Crop dry weight	Grain yield	Stover yield
	Score	Effect on crop	(g m^{-2})	(q ha^{-1})	(q ha^{-1})
T_1	0	No injury	478^{bc}	4.40^{bc}	12.5^{ab}
T_2	1	Slight stunting, discoloration	406^{b}	4.36^{bc}	13.3^{bcd}
T_3	1	Slight stunting, discoloration	444^{bc}	4.53^{bc}	13.6^{bcd}
T_4	1	Slight stunting, discoloration	473^{bc}	4.20^{b}	15.3^{de}
T_5	2	Stunting and discoloration	450^{bc}	4.29^{b}	20.0^{f}
T_6	0	No injury	413^{b}	4.71^{bd}	11.7^{bc}
T_7	0	No injury	439^{bc}	5.21^{cde}	14.2^{cd}
T_8	0	No injury	513^{c}	5.53^{de}	18.0^{ef}
T_9			519^{c}	5.87^{e}	19.3^{f}
T_{10}			327^{a}	3.40^{a}	10.0^{a}
T_{11}			613^{d}	6.92^{f}	23.9^{g}

Treatment details are described in Table 1; Means superscripted with different letters are significant at p<0.05 as per Tukey's HSD test; NS- Non-significant; [a]Values against T_8 are mean of two-year data.

Table 4: Economics of different weed management practices in moth bean (mean of three-year data)[a].

Treatment	*Gross returns (Rs. ha^{-1}) (a)	Cost of herbicide (Rs. ha^{-1}) (b)	Sprayer rent (Rs. ha^{-1}) (c)	**Labour cost (Rs. ha^{-1}) (d)	Total variable cost (Rs. ha^{-1}) e=(b+c+d)	***Total cost of cultivation (Rs. ha^{-1}) (Rs. 9000+d)	Net benefit (Rs. ha^{-1}) (a-e)
T_1	19880	1193	500	600	2293	11293	17587
T_2	20571	600	500	600	1700	10700	18871
T_3	21295	1550	500	600	2650	11650	18645
T_4	20548	1600	500	600	2700	11700	17848
T_5	22298	2000	500	600	3100	12100	19198
T_6	21408	1071	500	600	2171	11171	19237
T_7	24051	1400	500	600	2500	11500	21551
T_8	26421	1786	500	600	2886	11886	23535
T_9	28071	0	0	3000	3000	12000	25071
T_{10}	11539	0	0	0	0	9000	11539
T_{11}	33465	0	0	6000	6000	15000	27465

*Seed price @ Rs 3800 q^{-1}; stover price @ Rs 200 q^{-1}; **Labour cost @ Rs. 300 man day^{-1}; ***Cost of cultivation of moth bean except weed management- Rs. 9000 ha^{-1}, [a]Values against T_8 are mean of two years data.

dry weight (513 g m^{-2}). Thus, the variation in crop dry weight under different herbicides was ascribed both due to effective weed control and the phytotoxic effect of imazethapyr on moth bean. The significant difference in crop growth under the different magnitude of crop-weed interference resulted in significant differences in the yields of moth bean (Table 3). On the other hand, the favourable environment provided due to the higher weed control efficacy of imazethapyr-containing treatments (T_2, T_3, T_4 and T_5) was suppressed by the phytotoxic effect on moth bean and it was manifested in the growth and yield of the crop.

Because of its at par weed control efficacy and no phytotoxic effect on moth bean, clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8) being at per with hand weeding (T_9), recorded significantly higher seed yield (5.53 q ha^{-1}) over imazethapyr containing treatments (T_2, T_3, T_4 and T_5) and pendimethalin (T_1). However, in terms of stover yield, clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8) was found at par with propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_5) and hand weeding (T_9). The higher yield under these treatments might be due to effective control of the weeds as indicated through higher WCE. Clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8) produced 162.4% and 180.0% higher seed yield and stover yield over unweeded, respectively. In this study, weed competition and crop phytotoxicity have manifested in crop growth and yields.

Economics

The higher seed and stover yield recorded under weed-free (T_{11}) treatment resulted in the highest gross returns and net benefits of moth bean, which was closely followed by hand weeding (T_9)(Table 4). These results corroborated with the finding of Ram Pratap *et al*. (2018). The weed management in moth bean, either through hand weeding or effective PoE herbicides (T_8), accounts for around 24-25% of the cost of cultivation. Although imazethapyr-containing herbicides (T_2, T_3, T_4 and T_5) have been more effective on weeds, as evidenced through WCE (Table 5), their crop phytotoxic effect resulted in low yields, therefore, low gross returns and net benefit. Thus, the highest gross returns (Rs. 26421 ha^{-1}) and net benefits (Rs. 23535 ha^{-1}) of moth bean were recorded under clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8).

Table 5: Impact assessment indices of herbicide treatments.

Treatment	WCE (%)	WI	HEI	WPI	CRI
T_1	40.8	36	1.5	1.38	2.55
T_2	69.4	37	2.9	1.04	4.36
T_3	67.6	34	2.7	1.06	4.2
T_4	71	39	2.6	1.08	4.05
T_5	73.8	38	3.0	1.03	4.31
T_6	41.4	32	1.6	1.09	2.16
T_7	59.7	25	2.9	1.08	3.3
T_8	66.3	20	3.9	1.05	4.7
T_9	71.9	15	-	-	-
T_{10}	0	65	-	-	-
T_{11}	100	-	-	-	-

Treatment details are described in Table 1.

Impact assessment indices

The significant difference in weed dry matter in different weed management practices was manifested in WCE and WI (Table 5). The better control of both grassy and broad-leaved weed under propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_5) results in the highest WCE (73.8%). However, due to the crop phytotoxic effect of imazethapyr, the minimum value of WI (20) was recorded in clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8). It reflects the effectiveness of applied herbicide in securing yield loss against weed competition and a lower value of WI means high herbicide efficiency.

As for efficient weed management, lower WPI and higher HEI values are desirable. Clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8) recorded the highest HEI (3.9), indicating the higher yield advantage (Table 5). The lowest WPI was recorded in propaquizafop + imazethapyr (PoE 125 g a.i. ha^{-1}) (T_{10}) (1.03). The highest CRI (4.70) was recorded in clodinafop-propargyl + sodium acifluorfen (PoE 312.5 g a.i. ha^{-1}) (T_8). This might have been due to satisfactory weed control under this treatment and no phytotoxic effect on the crop. These results corroborate the findings of Kumar *et al*. (2018).

CONCLUSION

The promising herbicides molecule for post-emergence application in *Kharif* pulses like imazethapyr causes phytotoxicity to moth bean resulted in lower yield and economic returns. Alternatively, post-emergence application of clodinafop-propargyl + sodium acifluorfen @ 312.5 g a.i. ha^{-1} was found to manage weed spectrum on par with imazethapyr herbicides and recorded significantly higher crop growth, yield and net benefits of moth bean in western arid regions of India.

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