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Herbicidal management of the invasive joyweed *Alternanthera bettzickiana*

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Abstract

Alternanthera bettzickiana is an invasive weed which has now attained the status of a major weed in several upland crops in Kerala. Field experiments were conducted in 2021 and 2022 to study the efficacy of various pre- emergence and post- emergence herbicides in controlling the weed in oriental pickling melon. Ten treatments included pre-emergence spray of oxyfluorfen and pendimethalin, post-emergence application of 2,4-D and metsulfuron methyl+ chlorimuron ethyl, oxyfluorfen and pendimethalin followed by 2,4-D and metsulfuron methyl+ chlorimuron ethyl, hand weeding at 20 and 40 DAS and unweeded control. Randomized block design was adopted and all the treatments were replicated thrice. Results indicated that dry matter production of *A. bettzickiana*, total weed dry matter production and nutrient uptake by weeds were significantly lower with pre-emergence application of oxyfluorfen followed by post-emergence application of 2,4-D or metsulfuron methyl+ chlorimuron ethyl and were on par with hand weeding at 20 DAS and 40 DAS. These treatments also resulted in higher crop growth, mean fruit weight and fruit yield. At 30 DAS, the same treatments as well as pre- emergence oxyfluorfen resulted in higher weed control efficiency, while at 60 DAS, only the combined pre- and post- emergence application of oxyfluorfen followed by 2,4-D or metsulfuron methyl+ chlorimuron ethyl resulted in higher weed control efficiency. The combinations also recorded lower weed index and higher net return and B: C ratio.

Key words: 2,4-D, Metsulfuron methyl+ chlorimuron ethyl, Oxyfluorfen, Pendimethalin, Weed control efficiency, Weed index.

Introduction

Invasion of agricultural fields, forests and aquatic ecosystems by alien weed species is fast becoming a global concern. *Alternanthera bettzickiana*, commonly known as Calico plant, is an invasive upland weed belonging to the family Amaranthaceae. Alternanthera, various species of which are often known as joyweeds, is a genus of plants that is prevalent in almost all continents in the world and *Alternanthera bettzickiana* is a relatively recent entrant to this family. Originating in tropical America, it has extended its habitat to various parts of the world, and in Kerala, it is currently appearing as a major weed in wastelands and in several upland crops like fruits, vegetables and tuber crops and has now reached alarming proportions.

Among different weed control methods, use of herbicides is widely practiced for management of invasive weeds as it offers quick control, preventing their rapid spread, and need less labour when compared to physical and chemical methods (Clout and Williams, 2009). Complete control of weeds cannot be achieved by using a single weed control method or single herbicide. Under such conditions, pre- and post-emergence herbicides applied in sequence will control the weeds very effectively.

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Due to varied modes of action, sequential application of herbicides enable long-term control of weed infestations and broaden the control spectrum. (Costa et al., 2020). Pre-emergence herbicides aid in preventing the emergence and establishment of weeds, whereas post-emergence herbicides facilitate the control of already established population. In this background an investigation was undertaken to assess the efficacy of various pre- and post-emergence herbicides, both alone and in an integrated manner, in order to develop an effective strategy for the management of *A. bettzickiana* before it reaches dangerous proportions.

Materials and methods

Field trials were conducted in 2021 and 2022 from July-August to October-November at Agronomy Farm, College of Agriculture, Vellanikkara which is located at 10º31'N latitude and 76º13'E longitude at an altitude of 40.3 m above mean sea level. The experiment was laid out in a field where high infestation of *Alternanthera bettzickiana* was observed regularly. Soil of the experimental area was sandy loam in texture and was acidic with a pH of 5.2 and having available nitrogen, phosphorus and potassium contents of 182 kgha^{-1}, 31 kg ha^{-1}and 216 kg ha^{-1}, respectively. Oriental pickling melon (variety Saubhagya) was raised as the test crop. The experiment was laid out in randomized block design and each treatment was replicated thrice. The ten treatments included pre-emergence application of oxyfluorfen, pre-emergence application of pendimethalin, post-emergence application of 2,4-D, post-emergence application of pre-mix commercial formulation of metsulfuron methyl+ chlorimuron ethyl, pre-emergence oxyfluorfen followed by post-emergence 2,4-D, pre-emergence oxyfluorfen followed by post-emergence

Table 1. Effect of herbicidal treatments on dry matter production of *A. bettzickiana* and total weeds at 30 DAS and 60 DAS

Treatments	30 DAS						60 DAS					
	DMP of *A. bettzickiana* (g m^{-2})			Total weed DMP(g m^{-2})			DMP of *A. bettzickiana* (g m^{-2})			Total weed DMP(g m^{-2})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1- Pre-emergence oxyfluorfen	0.93*^{c}	0.96^{c}	0.94^{c}	2.59^{c}	2.35^{c}	2.46^{d}	2.02^{c}	2.02^{de}	2.08^{c}	6.24^{e}	7.06^{e}	6.64^{e}
	(0.4)	(0.47)	(0.43)	(7.4)	(5.6)	(1.2)$^{\#}$	(3.73)	(4.1)	(3.91)	(39.2)	(49.8)	(44.5)
T_2-Pre-emergence pendimethalin	1.64^{b}	1.67^{b}	1.65^{b}	5.38^{b}	5.58^{b}	5.48^{c}	3.04^{b}	2.60^{c}	2.86^{b}	9.49^{c}	9.33^{c}	9.40^{c}
	(2.27)	(2.33)	(2.3)	(29.0)	(31.2)	(5.28)	(8.77)	(6.77)	(7.76)	(90)	(87.2)	(88.6)
T_3- Post-emergence 2,4-D	3.57^{a}	4.46^{a}	4.02^{a}	8.56^{a}	8.76^{a}	8.65^{b}	2.76^{b}	3.59^{b}	3.2^{b}	11.15^{b}	10.5^{b}	10.6^{b}
	(12.8)	(19.5)	(16.1)	(73.3)	(76.9)	(13.2)	(7.13)	(13.1)	(10.1)	(125)	(112)	(118.4)
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	3.94^{a}	4.09^{a}	4^{a}	8.92^{a}	8.79^{a}	8.85^{b}	2.88^{b}	3.86^{b}	3.4^{b}	10.78^{b}	10.9^{b}	10.8^{b}
	(15.07)	(16.6)	(15.8)	(79.7)	(77.9)	(14)	(7.83)	(15)	(11.4)	(116)	(120.3)	(118.3)
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	0.88^{c}	0.92^{c}	0.89^{c}	2.13^{c}	2.18^{c}	2.15^{d}	1.02^{e}	1.40^{f}	1.29^{d}	5.05^{f}	4.96^{f}	5^{f}
	(0.33)	(0.37)	(0.35)	(4.6)	(4.9)	(0.83)	(0.73)	(2)	(1.36)	(25.6)	(24.8)	(25.1)
T_6- Pre-em oxyfluorfen fb post- em met. methyl+chlor. ethyl	0.93^{c}	0.88^{c}	0.90^{c}	2.68^{c}	2.11^{c}	2.39^{d}	1.13^{de}	1.55^{ef}	1.41^{cd}	5.40^{ef}	5.05^{f}	5.22^{f}
	(0.47)	(0.33)	(0.4)	(7.2)	(4.8)	(1.13)	(0.87)	(2.47)	(1.66)	(29.2)	(25.7)	(27.4)
T_7- Pre-em pendimethalin fb post-em 2, 4-D	1.62^{b}	1.65^{b}	1.63^{b}	5.80^{b}	5.88^{b}	5.84^{c}	1.48^{cde}	2.08^{cde}	1.84^{cd}	7.57^{d}	7.96^{d}	7.76^{d}
	(2.13)	(2.37)	(2.25)	(33.8)	(34.7)	(6.05)	(1.80)	(4.37)	(3.08)	(57.5)	(63.7)	(60.5)
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	1.72^{b}	1.69^{b}	1.7^{b}	5.94^{b}	5.74^{b}	5.81^{c}	1.60^{cd}	2.24^{cd}	1.97^{cd}	7.78^{d}	8.20^{d}	7.99^{d}
	(2.50)	(2.53)	(2.51)	(35.4)	(33.1)	(6.14)	(2.07)	(5.07)	(3.56)	(61)	(67.3)	(64.1)
T_9- Hand weeding at 20 and 40 DAS	1.17^{bc}	1.14^{bc}	1.15^{c}	2.31^{c}	2.51^{c}	2.41^{d}	1.34^{de}	1.73^{def}	1.60^{cd}	5.24^{f}	4.53^{f}	4.88^{f}
	(0.87)	(0.80)	(0.83)	(5.4)	(6.3)	(1.01)	(1.30)	(3.03)	(2.16)	(27.5)	(20.7)	(24.1)
T_{10}- Unweeded control	4.11^{a}	4.39^{a}	4.24^{a}	9.23^{a}	9.44^{a}	9.33^{a}	8.26^{a}	7.46^{a}	7.65^{a}	14.19^{a}	14.31^{a}	14.2^{a}
	(16.4)	(18.8)	(17.6)	(85.3)	(89.4)	(15.4)	(60.6)	(55.9)	(58.2)	(202)	(205)	(203.2)
SEm	0.41	0.48	0.44	0.90	0.93	0.91	0.67	0.57	0.59	0.96	0.98	0.97
CD (0.05)	0.63	0.68	0.46	0.72	0.98	0.42	0.56	0.58	0.77	0.93	0.58	0.76

*$\sqrt{(x+0.5)}$ transformed values, original values in parentheses. In a column, means followed by same letters do not differ significantly # Aitken transformation applied for achieving homogeneity of values across the years,

metsulfuron methyl+ chlorimuron ethyl, pre-emergence pendimethalin followed by post-emergence 2,4-D, pre- emergence pendimethalin followed by post-emergence metsulfuron methyl+ chlorimuron ethyl, hand weeding at 20 DAS and 40 DAS, and unweeded control.

Plots of size 20 m^2 were formed and pits of 60 cm diameter and 30 cm depth were made at a spacing of 2 m x 1.5 m. Gap filling and thinning were done two weeks after sowing to remove unhealthy plants and to maintain a population of three plants per pit. A fertilizer dose of 70: 25: 25 kg N, P_2O_5 and K_2O $ha^{-1}$was applied in the field as per the package of practices of the Kerala Agricultural University (KAU, 2016). In hand weeded plots, manual weeding was done at 20 DAS and 40 DAS. Application of pre-emergence herbicides was done on the day of sowing and post-emergence application as directed spray at one month after sowing in the interspaces of the crop. Dry matter production of *A. bettzickiana* and total weed dry matter production (g m^{-2}) were observed at 30 DAS and 60 DAS. Total nutrient removal by weeds was worked out by multiplying nutrient content in weeds with weed dry matter production and expressed in kg ha^{-1}. Weed control efficiency (WCE) was worked out using the formula given by Mani and Gautham (1973) and weed index (WI) was calculated based on the formula proposed by Gill (1969) and expressed in percentage.

$$\text{WCE (\%)} = \frac{\text{WDMP in the control plot} - \text{WDMP in treatment plot}}{\text{WDMP in the control plot}} \text{X } 100$$

*WDMP- Weed dry matter production

Table 2. Effect of herbicidal treatments on total nutrient removal by weeds at 30 DAS

Treatments	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1- Pre-emergence oxyfluorfen	1.15^c	0.95^d	1.04^f	0.14^{cde}	0.10^{bc}	0.12^d	0.72^c	0.62^c	0.66^{de}
T_2-Pre-emergence pendimethalin	5.21^b	5.69^c	5.44^e	0.36^{cd}	0.40^{bc}	0.38^c	2.05^b	2.24^b	2.15^c
T_3- Post-emergence 2,4-D	9.81^a	10.5^a	10.1^b	1.33^b	1.52^a	1.42^b	5.19^a	5.39^a	5.29^{ab}
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	9.25^a	9.17^{ab}	9.21^c	1.46^{ab}	1.61^a	1.53^b	5.21^a	5.02^a	5.15^b
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	1.00^c	1.21^d	1.11^f	0.08^{de}	0.09^c	0.07^d	0.43^c	0.38^c	0.42^e
T_6- Pre-em oxyfluorfen fb post-em met. methyl+chlor. ethyl	1.12^c	0.81^d	0.96^f	0.09^{de}	0.07^c	0.08^d	0.51^c	0.32^c	0.40^e
T_7- Pre-em pendimethalin fb post-em 2, 4-D	5.57^b	5.91^{bc}	5.74^e	0.40^b	0.44^b	0.42^c	2.10^b	2.18^b	2.13^c
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	6.54^b	6.48^{bc}	6.51^d	0.39^b	0.37^{bc}	0.36^c	2.22^b	2.07^b	2.14^c
T_9- Hand weeding at 20 and 40 DAS	1.04^c	1.21^d	1.12^f	0.07^e	0.08^c	0.08^d	0.45^c	0.52^c	0.48^{de}
T_{10}- Unweeded control	10.7^a	11.1^a	10.8 ^{a}	1.74^a	1.86^a	1.8^a	5.30^a	5.92^a	5.61^a
SEm	2.10	1.29	1.25	0.21	0.22	0.21	0.65	0.69	0.66
CD (0.05)	2.18	3.42	0.52	0.28	0.34	0.13	0.96	0.97	0.39

In a column, means followed by same letters do not differ significantly

Table 3. Effect of herbicidal treatments on total nutrient removal by weeds at 60 DAS

Treatments	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1- Pre-emergence oxyfluorfen	6.75^d	8.5^{de}	7.62d^e	0.79^c	0.97^{bc}	0.88^c	3.55^{ef}	4.50^{de}	4.02^e
T_2-Pre-emergence pendimethalin	14.5^{bc}	15.6^b	15^b	1.25^b	1.20^b	1.22^b	7.42^c	7.26^c	7.34^c
T_3- Post-emergence 2,4-D	17.3^b	15.3^{bc}	16.3^b	2.36^a	2.12^a	2.23^a	12.2^b	10.9^b	11.6^b
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	16.3^b	13.9^{bc}	15.2^b	2.20^a	2.33^a	2.26^a	10.7^b	11.1^b	10.8^b
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	4.98^d	3.91^e	4.44^f	0.43^d	0.47^d	0.45^d	2.97^f	2.88^{ef}	2.92^{ef}
T_6- Pre-em oxyfluorfen fb post-em met. methyl+chlor. ethyl	5.59^d	5.37^e	5.47^{ef}	0.41^d	0.36^d	0.38^d	2.83^f	2.53^f	2.70^f
T_7- Pre-em pendimethalin fb post-em 2, 4-D	9.54^{cd}	10.5^{cd}	10.0^{cd}	0.79^c	0.85^c	0.81^c	5.19^{de}	5.67^{cd}	5.42^d
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	10.3^{cd}	12.6^{bcd}	11.4^c	0.82^c	0.91^{bc}	0.86^c	5.51^d	6.06^{cd}	5.78^d
T_9- Hand weeding at 20 and 40 DAS	5.27^d	3.92^e	4.59^f	0.40^d	0.31^d	0.35^d	3.0^f	2.28^f	2.63^f
T_{10}- Unweeded control	25.2^a	22.7^a	23.9^a	2.54^a	2.33^a	2.43^a	15.7^a	16.3^a	15.8^a
Sem	2.1	1.9	2.0	0.27	0.25	0.26	1.40	1.45	1.42
CD (0.05)	5.54	4.97	2.82	0.36	0.31	0.22	1.73	1.64	1.71

In a column, means followed by same letters do not differ significantly

$$\text{WI (\%)} = \frac{\text{Yield in hand weeded plot} - \text{Yield in treatment plot}}{\text{Yield in hand weeded plot}} \times 100$$

Dry matter production of oriental pickling melon was recorded at 30 DAS and 60 DAS and at harvest. Yield attributes and yield of the crop were recorded at harvest. Data of the two years of field trials were pooled.

Data on weed dry weight were subjected to square root transformation ($\sqrt{(x+0.5)}$) so as to make analysis of variance valid (Gomez and Gomez, 1984). Statistical software GRAPES 1.1.0 was used for data pooling and data analysis (Gopinath et al., 2021).

Results and discussion

Weed spectra

Alternanthera bettzickiana, Borreria hispida, *Mitracarpus verticillatus* and *Synedrella nodiflora* were the major broad-leaved weeds in both the years. Major grasses included *Panicum maximum*, *Dactyloctenium aegyptium* and *Digitaria sanguinalis*. Sedges were absent in the field.

Weed dry matter production

Data on dry matter production of *A. bettzickiana* and that of total weed population at 30 DAS and 60 DAS are presented in Table 1. In both the years, at 30 DAS, significantly lower dry matter production

Table 4. Effect of herbicidal treatments on dry matter production of oriental pickling melon at 30 DAS, 60 DAS and at harvest

Treatments	30 DAS (g per plant)			60 DAS (g per plant)			Harvest (g per plant)		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1- Pre-emergence oxyfluorfen	4.20^{a}	5.24^{ab}	4.72^{a}	30.5^{bc}	36.7^{bc}	33.6^{c}	41.4^{cd}	50.9^{b}	46.1^{bc}
T_2-Pre-emergence pendimethalin	2.82^{b}	4.38^{c}	3.60^{b}	26.4^{cd}	33.6^{cd}	30.0^{d}	39.2^{cde}	44.5^{bc}	41.8^{c}
T_3- Post-emergence 2,4-D	1.69^{c}	2.80^{d}	2.24^{c}	23.5^{d}	29.4^{de}	26.4^{e}	29.4^{def}	34.8^{cd}	32.1^{d}
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	1.71^{c}	2.88^{d}	2.29^{c}	22.9^{d}	27.6^{de}	25.2^{e}	27.8^{ef}	31.3^{d}	29.5^{de}
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	4.18^{a}	5.54^{a}	4.86^{a}	44.4^{a}	51.9^{a}	48.1^{a}	58.3^{a}	68.5^{a}	63.4^{a}
T_6- Pre-em oxyfluorfen fb post-em met. methyl+chlor. ethyl	4.27^{a}	5.27^{a}	4.77^{a}	45.6^{a}	49.7^{a}	47.6^{a}	55.0^{ab}	66.2^{a}	60.6^{a}
T_7- Pre-em pendimethalin fb post-em 2, 4-D	2.59^{bc}	4.42^{c}	3.50^{b}	33.6^{b}	40.8^{b}	37.1^{b}	44.7^{bc}	55.6^{b}	50.1^{b}
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	2.89^{b}	4.49^{bc}	3.69^{b}	31.7^{bc}	39.2^{bc}	35.3b^{c}	42.7^{bcd}	53.5^{b}	48.1^{b}
T_9- Hand weeding at 20 and 40 DAS	4.13^{a}	5.36^{a}	4.74^{a}	45.4^{a}	52.6^{a}	49.0^{a}	60.0^{a}	69.0^{a}	64.5^{a}
T_{10}- Unweeded control	1.76^{c}	2.46^{d}	2.11^{c}	16.3^{e}	23.5^{e}	19.9^{f}	24.7^{f}	29.5^{d}	27.1^{e}
Sem	0.0.35	0.37	0.29	3.26	3.27	3.26	4	4.76	4.14
CD (0.05)	0.91	0.76	0.74	6.31	6.11	2.02	13.4	9.67	4.72

In a column, means followed by same letters do not differ significantly

Table 5. Effect of herbicidal treatments on yield attributes and yield of oriental pickling melon

Treatments	No. of fruits per plant			Fruit weight (g)			Yield (t ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
T_1- Pre-emergence oxyfluorfen	4.0	4.5	4.25	807^{abc}	833^{abc}	820^{b}	15.5^{bcd}	19.2^{ab}	17.3^{c}
T_2-Pre-emergence pendimethalin	3.2	3.8	3.50	690de	780^{cd}	735^{c}	11.0^{de}	14.9^{bcd}	13.0^{e}
T_3- Post-emergence 2,4-D	2.3	3.5	2.90	620^{f}	643^{e}	632^{d}	7.2^{e}	11.3^{cd}	9.3^{f}
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	2.5	3.2	2.85	593^{ef}	677de	635^{d}	7.4^{e}	10.7^{d}	9.1^{f}
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	3.8	4.7	4.25	900^{a}	938^{ab}	919^{a}	19.7^{ab}	22.6^{a}	21.2^{a}
T_6- Pre-em oxyfluorfen fb post-em met. methyl+chlor. ethyl	3.7	4.3	4.00	897^{a}	927^{ab}	912^{a}	19.1^{ab}	21.9^{a}	20.5^{a}
T_7- Pre-em pendimethalin fb post-em 2, 4-D	3.0	3.8	3.40	780b^{cd}	858^{abc}	819^{b}	15.3^{bcd}	18.5^{ab}	16.9^{cd}
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	3.5	4.3	3.90	775^{cd}	820^{bc}	798^{b}	14.4^{cd}	17.3^{abc}	15.8^{cd}
T_9- Hand weeding at 20 and 40 DAS	4.2	4.8	4.50	893^{a}	950^{a}	923^{a}	20.6^{a}	23.2^{a}	21.9^{a}
T_{10}- Unweeded control	2.5	3.0	2.75	543^{f}	588^{e}	566^{e}	6.8^{e}	8.9^{d}	7.8^{g}
SEm	0.21	0.19	0.2	41.1	41	41	1.65	1.63	1.7
CD (0.05)	NS	NS	-	96.75	122	36.9	4.67	6.35	1.19

In a column, means followed by same letters do not differ significantly of *A. bettzickiana* and total weeds were recorded with pre-emergence application of oxyfluorfen and was on par with hand weeding at 20 DAS and 40 DAS. Pooled analysis also displayed significantly lower dry matter production of weeds with pre-emergence application of oxyfluorfen (0.43g m^{-2}). Prevention of seedling emergence due to the application of oxyfluorfen reduced the density of weeds and thereby the dry matter production, and a similar result was reported by Ramalingam et al. (2013) who observed 70 per cent to 90 per cent reduction in the density of broad-leaved weeds with pre-emergence application of oxyfluorfen. Singh et al. (2017) also observed minimum weed density and dry matter production with pre-emergence application of oxyfluorfen at the rate of 0.2 kg ha^{-1} in brinjal. Higher dry weight of *A. bettzickiana* (17.6 g m^{-2}) and total weed dry matter production(15.4g m^{-2}) at 30 DAS were recorded in unweeded control. Among the herbicidal treatments, post-emergence application of metsulfuron methyl+ chlorimuron ethyl and 2, 4-D recorded higher weed dry weight as these chemicals were applied only at 30 DAS by which time there was an initial flush of weeds similar to that in unweeded control.

Significantly lower dry weight of *A. bettzickiana* and total weed dry matter production at 60 DAS were recorded with pre-emergence application of oxyfluorfen followed by post-emergence application of 2,4-D, pre-emergence application of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl and hand weeding at 20 DAS and 40 DAS in both the years and in the pooled analysis. Pooled data showed that dry matter production of *A. bettzickiana* was 98 per cent, 97 per cent and 96 per cent lower in these treatments than that of unweeded control. Kundu et al. (2018) reported lower density and dry weight of broad-leaved weeds at 60 DAS due to post-emergence application of 2, 4-D ethyl ester in potato, and Kaur et al. (2017) observed lower biomass production of broad- leaved weeds at 45 and 70 days after transplanting in rice with the application of metsulfuron methyl + chlorimuron ethyl at the rate of 4 g ha^{-1}. Pre-emergence application of oxyfluorfen prevents the germination and growth of weeds and any broad-leaved weeds or sedges that emerge in the later stages are controlled by the post-emergence application of 2, 4-D or metsulfuron methyl + chlorimuron ethyl as directed spray, leading to lower total weed biomass production.

Nutrient removal by weeds

Pre-emergence application of oxyfluorfen resulted

Table 6.Weed Control Efficiency of pre- and post-emergence herbicides at 30 and 60 DAS, Weed Index and economics of cultivation

Treatments	Weed Control Efficiency (%)						Weed Index (%)			Net return (Rs./ha)		B:C ratio	
	30 DAS			60 DAS									
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled	2021	2022	2021	2022
T_1- Pre-emergence oxyfluorfen	91.1	93.5	92.6	80.5	75.6	78.1	24.8	17.2	21.0	79657	125757	1.65	2.02
T_2-Pre-emergence pendimethalin	66.1	64.8	65.5	55.1	57.5	56.3	46.6	35.8	41.2	18257	68957	1.15	1.55
T_3- Post-emergence 2,4-D	13.6	12.9	13.3	38.2	45.6	41.9	65.0	51.3	58.2	-29543	23757	0.76	1.19
T_4- Post-emergence metsulfuron methyl+ chlorimuron ethyl	6.4	10.0	8.2	41.9	41.2	41.6	64.1	53.9	59.0	-27243	15657	0.78	1.13
T_5- Pre-emergence oxyfluorfen fb post-emergence 2,4-D	94.6	94.4	94.5	87.3	87.9	87.6	4.40	2.60	3.50	129632	167332	2.03	2.32
T_6- Pre-em oxyfluorfen fb post-em met. methyl+chlor. ethyl	91.6	94.9	93.3	85.4	87.5	86.5	7.28	5.60	6.43	121532	157932	1.95	2.24
T_7- Pre-em pendimethalin fb post-em 2, 4-D	60.5	61.1	60.8	71.4	69.1	70.3	25.7	20.3	23.0	71532	113132	1.56	1.89
T_8- Pre-em pendimethalin fb post-em met. methyl+chlor. ethyl	58.6	61.9	60.3	69.7	67.0	68.4	30.1	25.4	27.8	59532	97232	1.47	1.76
T_9- Hand weeding at 20 and 40 DAS	93.6	92.9	93.3	86.2	90.0	88.1	-	-	-	113532	147332	1.74	1.94
T_{10}- Unweeded control	-	-	-	-	-	-	67.0	61.6	64.3	-32118	-6118	0.73	0.95

in lower nitrogen, phosphorus and potassium removal by weeds at 30 DAS, and was statistically on par with hand weeding at 20 DAS and 40 DAS in both the years and in pooled analysis (Table 2). Among the herbicidal treatments, pre-emergence application of oxyfluorfen followed by post-emergence application of 2, 4-D and pre-emergence application of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl recorded lower nutrient removal by the weeds when compared to other treatments at 60 DAS (Table 3) and the results were in agreement with the findings of Sable et al. (2013) who reported significantly lower N, P and K removal of 3.03, 0.47 and 2.34 kg ha^{-1} respectively at 40 DAS with pre-emergence application of oxyfluorfen in onion. Nutrient removal by a weed is the function of dry matter production and nutrient content of that weed. Therefore lower dry matter production of weeds in these treatments due to integrated application of efficient pre- and post-emergence herbicides might have resulted in lower nutrient removal. At 30 DAS, nitrogen, phosphorus and potassium removal by the weeds was recorded to be higher in unweeded control, post-emergence application of 2, 4-D and metsulfuron methyl+ chlorimuron ethyl, and at 60 DAS in unweeded control due to unrestrained growth and dry matter accumulation of weeds (Tables 2 and 3).

Dry matter production of oriental pickling melon

Among the herbicidal treatments, higher dry matter production of the crop at 30 DAS was recorded in pre-emergence application of oxyfluorfen which was on par with hand weeding at 20 DAS and 40 DAS in both the years and in pooled data (Table 4). Cohen et al. (2008) reported safe use of oxyfluorfen for weed control in grafted water melon resulted in higher biomass production by the crop. Lowest dry matter production of crop was observed in unweeded control (2.11 g per plant), post-emergence application of 2, 4-D (2.24 g per plant) and post-emergence application of metsulfuron methyl+ chlorimuron ethyl (2.29 g per plant) due to higher weed density leading to higher water and nutrient removal by the weeds, making them unavailable to the crop. Higher crop dry weight at 60 DAS and at harvest was observed with hand weeding (49 g and 64.5 g per plant), pre-emergence spray of oxyfluorfen followed by post-emergence spray of 2, 4-D (48.1 g and 63.4 g per plant) and pre-emergence spray of oxyfluorfen followed by post-emergence spray of metsulfuron methyl+chlorimuron ethyl (47.6 g and 60.6 g per plant) (Table 4), which can be attributed to relatively lower weed density and nutrient uptake by weeds associated with these treatments due to integrated application of pre- and post-emergence herbicides.

Yield attributes and yield

Yield loss in vegetables can be avoided by controlling weeds in the early stages of crop growth, despite the fact that different crops have varying levels of tolerance to weed competition (Zimdahl, 1980). Critical period of weed control in *Cucumis sativus* was up to four weeks after sowing during which weed infestation could drastically reduce the yield (Weaver, 1984). In this study, number of fruits produced per plant registered no significant variation among the treatments (Table 5). Data on individual fruit weight and total fruit yield pooled over two years showed that both these were significantly higher with hand weeding at 20 DAS and 40 DAS (923 g and 21.9 t ha^{-1}) and with pre-emergence application of oxyfluorfen followed by post-emergence application of 2, 4-D (919 g and 21.2 t ha^{-1}) and pre- emergence application of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl (912 g and 20.5 t ha^{-1}) (Table 5). These treatments resulted in a yield increase of 64 per cent, 63 per cent and 62 per cent respectively when compared to unweeded control. A similar result was reported by Carvalho et al. (2022) who reported that pre-emergence application of oxyfluorfen resulted in higher yield in melon (*Cucumis melo*) which was statistically on par with weed-free plots. Integration of efficient pre- and post-emergence herbicides restricts the growth of weeds throughout the cropping period, especially during the critical period of weed control, facilitating greater availability of nutrients and other resources to the crop, which ultimately leads to higher yield and this could be the reason for greater yield in pre-emergence application of oxyfluorfen followed by post-emergence application of 2, 4-Dor metsulfuron methyl+ chlorimuron ethyl.

Weed control efficiency and weed index
At 30 DAS, weed control efficiency was found to be higher in pre-emergence application of oxyfluorfen followed by post-emergence application of 2, 4-D (94.5 per cent), pre-emergence application of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl (93.3 per cent), hand weeding at 20 DAS and 40 DAS (93.3 per cent) and pre-emergence spray of oxyfluorfen (92.6 per cent) (Table 6). At 60 DAS, pre-emergence spray of oxyfluorfen followed by post-emergence application of 2, 4-D, pre-emergence application of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl and hand weeding resulted in higher weed control efficiency of 88.1 per cent, 87.6 per cent and 86.5 per cent, respectively in the pooled analysis (Table 6). Lower weed dry matter production recorded in these treatments compared to the unweeded control resulted in their higher weed control efficiency and is in accordance with findings of Ramachandiran and Balasubramanian (2012) who reported weed control efficiency of 92.6 per cent with pre-emergence application of oxyfluorfen followed by post-emergence application of 2, 4-D at 30 DAS in onion. Weed index represents the extent of reduction in yield due to the presence of weeds when compared with weed-free check and lower weed index indicates higher efficiency of the weed control method in increasing crop yield through reduction of weed competition. Lower weed index values of 3.5 per cent and 6.4 per cent were recorded in the above treatments and higher values were observed in unweeded control (64.3 per cent), post-emergence application of metsulfuron methyl+ chlorimuron ethyl (59 per cent) and post-emergence application of 2, 4-D (58.2 per cent) (Table 6).

Economics
An analysis of economics of cultivation of oriental pickling melon with various pre- and post-emergence herbicides adopted for weed controlrevealed that pre-emergence application of oxyfluorfen followed by post-emergence spray of 2, 4-D or metsulfuron methyl+ chlorimuron ethyl resulted in higher net return and B:C ratio in both the years than hand weeding at 20 DAS and 40 DAS (Table 6). Pre-emergence applicationof oxyfluorfen followed by post-emergence application of 2, 4-D resulted in net returnof Rs.1,29,632 and Rs.1,67,332 and B:C ratio of 2.03 and 2.32 in 2021 and 2022 respectively, while corresponding figures for pre-emergence spray of oxyfluorfen followed by post-emergence application of metsulfuron methyl+ chlorimuron ethyl were Rs.1,21,532 and Rs.1,57,932 and B:C ratio of 1.95 and 2.24. In 2021 and 2022, net return of the hand weeded plot were Rs.1,13,532 and Rs.1,47,332 respectively, while B:C ratio were 1.74 and 1.94, respectively. Therefore, chemical control of weeds including *A. bettzickiana* through the above mentioned herbicides are more economical than adopting hand weeding or application of pendimethalin or application of post-emergence herbicides alone.

Conclusion

Integrated application of, pre- and post-emergence herbicides provides more effective control of weeds including *Alternanthera bettzickiana* than their individual application. Pre-emergence applicationof oxyfluorfen followed by post-emergence application of 2, 4-D or metsulfuron methyl+ chlorimuron ethyl can be adopted for efficient and economic control of weeds in oriental pickling melon.

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