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RESEARCH ARTICLE

Weed management efficacy and rice nutrient uptake as influenced by pyrazosulfuron-ethyl + oxaziclomefone in transplanted rice

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ABSTRACT

An experiment was conducted at CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur during the *kharif* seasons of 2021 and 2022, to evaluate the weed management efficacy and rice nutrient uptake as influenced by pyrazosulfuron-ethyl 8.4% + oxaziclomefone 20% WP (pyrazosulfuron-ethyl and + oxaziclomefone) (ready-mix) in transplanted rice. The pre-emergence application (PE) of pyrazosulfuron-ethyl + oxaziclomefone at 21+50 g/ha was at par with its higher dose of 26.25+62.5 g/ha and also with weed-free check in significantly lowering total weed density and biomass at 30 and 45 days after transplanting with higher weed control efficiency and lower weed index. Lower removal of N, P and K by total weeds, higher uptake of N, P and K by rice crop, higher rice grain yield and straw yield were also recorded with pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5 and 21+50 g/ha, which were comparable to the uptake done by rice in weed free. Thus, pyrazosulfuron-ethyl + oxaziclomefone 21+50 g/ha PE was proved to be the most effective option for controlling weeds efficiently and producing higher rice productivity in transplanted rice.

Keywords: Bioefficacy, Nutrient uptake, Pyrazosulfuron + oxaziclomefone, Transplanted rice, Weed management

INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population. About 90% of the total rice is grown and consumed in Asia. Globally, this crop ranks first in area and second to wheat in total production. It is one of the most important food crop grown extensively in India and plays a key role in the livelihood, food and economic security of the farmer's and contributes to about 43% of total food grain production. India had 51 million hectares of land area under rice cultivation, with production and productivity of 150 million tons and 4.41 t/ha (Anonymous 2024a). In Himachal Pradesh, the area under rice was targeted at 88.16 thousand hectares with a production and productivity of 199 thousand tons and 2.2 t/ha, respectively (Anonymous 2024b).

Among the prominent factors responsible for the low productivity of rice in Himachal Pradesh, inadequate weed control is the major one. Weeds compete with rice due to their high adaptability, faster growth and dominate the crop habitat, resulting in reduced rice productivity (Rao *et al.* 2017). Weeds compete for nutrients, moisture, light and space with crop. As per an estimate, weeds can deprive the crops nutrient uptake of 47% N, 42% P, 50% K, 39% Ca and 24% Mg and reduce the yield potential by harbouring the number of crop pests. Keeping the fields weed free during the critical competition period is essential for obtaining optimum yield of rice. This can be achieved by removing weeds manually, mechanically, chemically or by their combinations. Weed growth is relatively less in transplanted rice compared to direct-seeded rice (Rao *et al.* 2007; Khare *et al.* 2014; Rao *et al.* 2015).

In the recent past, several pre-and post-emergence herbicides have been recommended for controlling weeds in rice, out of which butachlor and cyhalofop-butyl have been popular among farmers. However, pretilachlor and pyrazosulfuron have also become popular among the rice farmers in different areas. Herbicides like butachlor and pretilachlor used in rice fields are required in large dosages of active ingredients and these herbicides may leave more residues in the soil, which may deteriorate soil and human health (Cai *et al.* 2014).

Repeated use of any single herbicide in any crop results in the development of resistant weeds for particular weedicide and results in the shift of weed flora, leading to the dominance of secondary weeds (Chauhan 2012, Chauhan and Opena 2012). For instance, *Echinochloa crus-galli* has developed resistance to several herbicides, including butachlor

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and quinclorac, due to their continuous use in rice (Heap 2025). This necessitates using other herbicides that are quite effective against associated and resistant weeds. Moreover, for broader spectrum weed control, reduced phytotoxicity on crop and in efforts to inflict minimum harm to the environment, it is advantageous to enhance the herbicides efficacy by using herbicides mixtures for broader and effective weed management.

In view of this, newer herbicides that can be used at lower doses are being added each year to alleviate environmental and health concerns and meet stringent regulatory requirements. Similarly, in this context, a new ready-mix herbicide combination of pyrazosulfuron-ethyl and oxaziclomefone, a pre-emergence broad spectrum herbicide was reported to have efficacy to control grasses, sedges and broad-leaved weeds in different rice cultures (Shi *et al.* 2024). Pyrazosulfuron-ethyl belongs to the sulfonylurea chemical family and is classified under HRAC Group/ 2 (ALS inhibitors); it acts by inhibiting acetolactate synthase (ALS), disrupting the biosynthesis of branched-chain amino acids vital for protein synthesis and cell division (Ma et al. 2021). Oxaziclomefone, relatively newer, is an isoxazole family herbicide grouped under HRAC Group/ E (cell division inhibitors); it impedes microtubule assembly during mitosis, preventing cell division in germinating weed seedlings. The dual action—prevention of amino-acid synthesis and interruption of cell division—not only broadens weed spectrum control but also helps to delay resistance development and ensures crop safety and environmental compatibility. The component oxaziclomefone in this combination, blocks plant growth by inhibiting plant cell expansion in grass roots and pyrazosulfuron-ethyl which is a sulfonylurea herbicide, gives very good control of all three types of weeds (grassy, broad-leaved weeds and sedges) by inhibiting acetolactate synthase in transplanted rice (Ramesha *et al.* 2017a).

Thus, in this study a new herbicide combination product *i.e.* pyrazosulfuron-ethyl 8.4% + oxaziclomefone 20% WP (pyrazosulfuron-ethyl + oxaziclomefone) was tested and compared with other pre-emergent herbicides *viz.* pretilachlor and pyrazosulfuron applied either alone or in their combination. The objective of this study was to evaluate the weed management efficacy and rice nutrient uptake as influenced by pyrazosulfuron-ethyl + oxaziclomefone (ready-mix) in transplanted rice.

MATERIALS AND METHODS

The field experiments were conducted during the *Kharif* seasons of 2021 and 2022 at the Experimental Research Farm of the Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The experimental site is situated at latitude 32° 6' N, longitude 76° 3' E and altitude of 1290.8 m above mean sea level in the North-West Himalayan region.

The experiment consisting of eight weed control treatments *viz.* pre-emergence application (PE) of pyrazosulfuron-ethyl + oxaziclomefone at three doses *i.e.* 15.75+37.5, 21+50 and 26.25+62.5 g/ha; pyrazosulfuron-ethyl 70 WDG (pyrazosulfuron-ethyl) 21 g/ha; pretilachlor 50 EC (pretilachlor) 750 g/ha; pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG (pretilachlor + pyrazosulfuron-ethyl) 600+15 g/ha; weed free and weedy check. A randomized block design with three replications was used. The soil of the experimental field was silty clay loam (sand 20.7%, silt 42.6% and clay 36.3%) in texture having an acidic pH (5.28). The soil was with medium in available nitrogen (326.14 kg/ha), high in available phosphorus (23.65 kg/ha) and medium in available potassium (256.74 kg/ha). Rice variety 'PAC 807^{+}' was transplanted at a spacing of 20 cm × 15 cm and the rice crop was raised with a recommended package of practices except for treatments during both years. The net plot area was 9.69 m^2.

All herbicides were applied as pre-emergence at 3 days after transplanting (DAT) with a knapsack sprayer delivering a spray volume of 750 litres/ha using the flat-fan nozzle. The data on total weed density (no./m^2) and dry weight (weed biomass) were recorded at 30 and 45 DAT in each plot from randomly placed two quadrats of 0.5 m × 0.5 m. Total weeds were counted from that area and density was expressed as weed density (no./m^2). The collected weeds were sun-dried and then kept in an electric oven at 65 ^{0}C till the weight became constant and total weed biomass is expressed as g/m^2. The observed data were subjected to square root transformation using the formula $\sqrt{x+1}$, since the data on weed density and biomass showed high variation and the statistical analysis was done as per the procedures given by Gomez and Gomez (1984). The grain and straw yields of rice were recorded from the net plot area and were expressed into t/ha at 14% moisture content using the formula.

The samples of total weeds collected at 90 DAT were dried and used to estimate the N, P and K removal by total weeds and likewise, the samples of rice grain and straw were collected at harvest, dried in sun and then dried in an oven at 70 °C for estimation of nitrogen, phosphorus and potassium content by Li (1966).

Uptake of N, P and K by total weeds for individual treatment was determined by multiplying the values of respective nutrient content with the corresponding dry matter of total weeds.

RESULTS AND DISCUSSION

Effect on weeds

All the weed control treatments were proved to be significantly superior to the weedy check and significantly reduced both total weed density and biomass as reflected by their higher weed control efficiency and lower weed index values during both years **(Table 1)**. Complete removal of weeds was done in weed free.

Among herbicidal treatments, pyrazosulfuron + oxaziclomefone 21+50 g/ha and 26.25+62.5 g/ha were at par with each other in significantly lowering weed density and biomass in comparison to the rest of the treatments in both the years. Next best treatments were pyrazosulfuron + oxaziclomefone 15.75+37.5 g/ha and pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha with both having statistically similar efficacy in managing weeds. The superior efficacy of these treatments in reducing the weed density and biomass can be attributed to the broad-spectrum action of these herbicides, which effectively targeted a wide range of weeds. Pal (2012) also recorded significantly lower weeds density with pyrazosulfuron-ethyl 42 g/ha in transplanted rice. The combination provides prolonged control, reducing weed regrowth and competition with the rice crop.

Among the herbicide treatments, the highest WCE in the range of 96.72 to 100% was recorded by pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5 g/ha at both stages of observation and during both years of experimentation and followed by pyrazosulfuron-ethyl + oxaziclomefone at 21+50 g/ha having corresponding values in the range of 92.63 to 98.77%. The weedy check had lowest WCE, indicating unmanaged abundant weed growth.

Weed index (WI), which quantifies yield loss due to weed competition, was lowest under the weed-free condition. Among herbicide treatments, pyrazosulfuron-ethyl + oxaziclomefone at 26.25+62.5 g/ha, recorded lowest WI values of 1.81% in 2021 and 2.68% in 2022 and followed by pyrazosulfuron-ethyl + oxaziclomefone at 21+50 g/ha, with corresponding values of 2.94 and 1.79%, reflecting minimal yield loss. Pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha had higher WI (13.35 and 10.07%) than rest of other treatments. The weedy check recorded the highest WI (29.41 and 28.86%), indicating substantial yield loss due to severe weed competition.

Table 1. Effect of different weed control treatments on total weed density and biomass in transplanted rice (2021 and 2022)

Treatment	Total weed density (no./m^2)				Total weed biomass (g/m^2)			
	30 DAT		45 DAT		30 DAT		45 DAT	
	2021	2022	2021	2022	2021	2022	2021	2022
Pyrazosulfuron-ethyl + oxaziclomefone 15.75+37.5 g/ha	5.72(32.0)	5.19(26.7)	7.27(52.0)	5.72(32.0)	2.28(4.2)	2.11(3.4)	2.77(6.7)	2.57(5.7)
Pyrazosulfuron-ethyl + oxaziclomefone 21+50 g/ha	1.67(2.7)	1.67(2.7)	2.96(11.7)	2.19(6.7)	1.14(0.3)	1.07(0.2)	1.45(1.4)	1.31(1.8)
Pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5 g/ha	1.00(0.0)	1.00(0.0)	2.45(6.7)	1.41(1.3)	1.00(0.0)	1.00(0.0)	1.25(0.6)	1.20(0.4)
Pyrazosulfuron 21 g/ha	7.26(52.0)	5.61(30.7)	8.27(68.0)	6.50(41.3)	2.69(6.2)	2.22(4.0)	3.19(9.3)	2.93(7.6)
Pretilachlor 750 g/ha	7.15(50.3)	5.74(32.0)	8.23(66.7)	6.88(46.7)	2.65(6.1)	2.33(4.5)	3.18(9.1)	3.17(9.1)
Pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha	5.97(36.0)	4.32(18.7)	7.13(51.3)	5.80(33.3)	2.23(4.1)	1.89(2.7)	2.81(7.0)	2.66(6.2)
Weed free	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)
Weedy check	9.78(94.7)	9.28(85.3)	12.07(144.7)	10.87(117.3)	3.75(13.1)	3.74(13.0)	4.53(19.5)	5.05(24.6)
LSD (p=0.05)	1.22	1.00	2.26	1.61	0.36	0.28	0.60	0.49

LSD- least significant difference at the 5% level of significance, DAT- days after transplanting, the figures in the parentheses are the means of original values

Effect on rice yield

During both years, weed control treatments have recorded significantly higher grain and straw yields **(Table 1)**. The percentage increase in grain yield due to different weed control treatments over weedy check ranged from 21.3 to 41.5% and 23.5 to 40.2% during the first and second year of study, respectively, while the corresponding increase in straw yield was in the range of 18.4 to 36.9% and 21.3 to 33.3%.

Among herbicide treatments, the combination of pyrazosulfuron + oxaziclomefone 21+50 and 26.25+62.5 g/ha had significantly higher grain and straw yield of rice, during both years, over the rest of all treatments and were statistically equivalent to the weed free. The rice grain yield of rice recorded with pyrazosulfuron + oxaziclomefone 21+50 g/ha was 37.5 and 37.8% higher than that recorded with weedy check during the first and second year, respectively. The corresponding increase in straw yield was 23.5 to 40.2%. The same herbicide combination applied at a higher dose of 26.25+62.50 g/ha caused 36.5 to 38.9% increase in grain yield and 29.5 to 35.7% increase in straw yield over the weedy check during the first and second year, respectively. The increased rice grain and straw yield can be attributed to improved utilization of available nutrients, light, and water confirming the findings of Ramesha *et al.* (2017b).

All the other remaining weed control treatments, being at par among themselves, were found significantly superior over weedy checks with regard to recording high grain and straw yield of rice during both the years of study. In transplanted rice, pyrazosulfuron-ethyl was reported as the most effective herbicide for increasing grain yield (Patel *et al.* 2023; Gupta *et al.* 2023) and Gupta *et al.* (2023) reported pretilachlor 500 g/ha also as most effective herbicide.

Effect on nutrient uptake by weeds

All the weed control treatments resulted in significantly lower uptake of nutrients (N, P and K) by total weeds over weedy check during both the years of experimentation **(Table 2)**. Due to the complete control of weeds in weed free check by their removal, no uptake was made by the weeds during both the years. Among herbicidal treatments, significantly lower uptake of N, P and K by total weeds in rice was recorded with pyrazosulfuron +

Table 2. Effect of different weed control treatments on weed control efficiency, rice yield (grain and straw) and weed index (WI) in transplanted rice (2021 and 2022)

Treatment	Weed control efficiency (%) 30 DAT		Weed control efficiency (%) 45 DAT		Rice grain yield (t/ha)		Rice straw yield (t/ha)		Weed index (%)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Pyrazosulfuron-ethyl + oxaziclomefone 15.75+37.5 g/ha	67.76	73.44	65.76	76.96	3.79	3.98	5.59	4.40	14.25	10.96
Pyrazosulfuron-ethyl + oxaziclomefone 21+50 g/ha	97.47	98.77	92.99	92.63	4.29	4.39	6.19	4.75	2.94	1.79
Pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5 g/ha	100.00	100.00	96.72	98.17	4.34	4.35	6.30	4.66	1.81	2.68
Pyrazosulfuron 21 g/ha	52.14	69.52	52.61	68.99	3.76	3.96	5.55	4.34	14.93	11.41
Pretilachlor 750 g/ha	53.60	65.67	53.38	63.04	3.74	3.93	5.51	4.33	15.38	12.08
Pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha	68.76	79.21	63.92	74.60	3.83	4.02	5.50	4.36	13.35	10.07
Weed free	100.00	100.00	100.00	100.00	4.42	4.47	6.35	4.79	0.00	0.00
Weedy check	0.00	0.00	0.00	0.00	3.12	3.18	4.64	3.59	29.41	28.86
LSD (p=0.05)	-	-	-	-	0.37	0.26	0.43	0.36	-	-

LSD- least significant difference at the 5% level of significance, DAT- days after transplanting

Table 3. Effect of weed control treatments on N, P and K uptake (kg/ha) by total weeds in transplanted rice

Treatment	Nitrogen (kg/ha)		Phosphorus (kg/ha)		Potassium (kg/ha)	
	2021	2022	2021	2022	2021	2022
Pyrazosulfuron-ethyl + oxaziclomefone 15.75+37.5 g/ha	4.60	4.45	0.91	0.88	5.81	5.61
Pyrazosulfuron-ethyl + oxaziclomefone 21+50 g/ha	1.37	1.17	0.25	0.21	1.78	1.52
Pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5 g/ha	1.32	0.85	0.26	0.18	1.75	1.18
Pyrazosulfuron 21 g/ha	5.18	5.88	1.03	1.17	6.40	7.26
Pretilachlor 750 g/ha	6.05	6.54	1.15	1.24	7.60	8.20
Pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha	4.61	3.92	0.82	0.70	5.40	4.59
Weed free	0.00	0.00	0.00	0.00	0.00	0.00
Weedy check	14.47	14.09	2.59	2.53	17.93	17.47
LSD (p=0.05)	1.09	1.29	0.36	0.38	1.16	1.39

LSD- least significant difference at the 5% level of significance

Table 4. Effect of weed control treatments on nitrogen, phosphorus and potassium uptake (kg/ha) by transplanted rice (grain, straw and total)

Treatment	Nitrogen uptake (kg/ha)						Phosphorus uptake (kg/ha)						Potassium uptake (kg/ha)					
	Grain		Straw		Total		Grain		Straw		Total		Grain		Straw		Total	
	2021	2022	2021	2021	2022	2021	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Pyrazosulfuron-ethyl + oxaziclomefone 15.75+37.5 g/ha	48.4	51.3	40.1	31.5	88.5	82.8	6.4	6.8	12.9	10.1	19.3	16.9	8.4	9.2	70.2	54.9	78.6	64.1
Pyrazosulfuron-ethyl + oxaziclomefone 21+50 g/ha	52.1	53.7	43.8	33.6	95.9	87.3	6.9	7.0	15.3	11.7	22.2	18.8	10.5	11.2	78.7	59.8	89.3	71.0
Pyrazosulfuron-ethyl + oxaziclomefone 26.25+62.5g/ha	53.2	53.8	45.2	33.3	98.4	87.1	7.2	7.2	15.7	11.6	23.0	18.8	10.6	10.8	81.4	59.7	92.0	70.4
Pyrazosulfuron 21 g/ha	47.3	50.1	39.6	31.0	86.9	81.1	6.0	6.3	11.9	9.3	17.9	15.6	9.1	10.1	68.4	53.0	77.5	63.0
Pretilachlor 750 g/ha	47.8	50.6	38.2	30.0	86.0	80.6	5.8	6.1	12.0	9.5	17.8	15.5	8.8	9.6	67.0	52.2	75.7	61.8
Pretilachlor + pyrazosulfuron-ethyl 600+15 g/ha	48.3	50.8	39.0	30.9	87.3	81.8	5.9	6.2	12.0	9.5	17.9	15.7	9.1	9.8	67.7	53.3	76.9	63.2
Weed free	53.4	54.4	45.5	34.3	98.9	88.7	7.4	7.5	17.0	12.8	24.4	20.3	11.1	11.5	84.4	63.1	95.5	74.6
Weedy check	41.6	42.8	29.0	22.4	70.6	65.2	5.2	5.3	9.2	7.1	14.4	12.4	7.4	7.6	52.4	40.2	59.8	47.8
LSD (p=0.05)	4.3	2.4	4.1	2.2	5.5	3.1	0.9	0.7	2.3	1.4	2.6	1.7	1.3	0.9	5.5	5.0	5.9	5.2

LSD- least significant difference at the 5% level of significance

oxaziclomefone 21+50 and 26.25+62.5 g/ha PE, which were on par with each other statistically during both the years. These treatments resulted in the savings of 13.10 to 13.15 and 12.92 to 13.24 kg N/ha during the first year and second year, respectively. Similarly, the corresponding savings in phosphorus were 2.33 to 2.34 and 2.32 to 2.35 kg P/ha and 16.15 to 16.18 and 15.95 to 16.29 kg K/ha with these treatments.

Combination of pyrazosulfuron + oxaziclomefone 15.75+37.5 g/ha was at par with pretilachlor + pyrazosulfuron 600+15 g/ha were found to be the other best treatments, which have resulted in lower nutrient uptake of N, P and K by total weeds during both the years. Moreover, during the first year, for significantly reduced uptake of phosphorus and potassium, pyrazosulfuron 21 g/ha was also at par with those treatments and with pretilachlor 750 g/ha which had recorded significantly lower uptake of phosphorus by total weeds. These results correspond closely with the findings of Babar and Velayutham (2012).

Effect on nutrient uptake by rice

All weed control treatments were significantly superior over weedy check and recorded higher uptake of major nutrients *i.e.* N, P and K in grain and straw of rice, thereby total uptake by crop during both the years of experimentation **(Table 3)**. Pyrazosulfuron + oxaziclomefone 21+50 and 26.25+62.5 g/ha were at par with each other in recording significantly higher uptake of nitrogen, phosphorus and potassium by rice grain, straw and thus total by crop, which was statistically similar to the uptake done by the crop grown in weed free check.

Among the rest of the treatments, pyrazosulfuron + oxaziclomefone 15.75+37.5 g/ha had significantly higher uptake of nitrogen and phosphorus by rice grain and straw which was at par to the above said superior treatments, during both the years. The significantly higher uptake of nitrogen, phosphorus and potassium by the rice crop with pyrazosulfuron + oxaziclomefone 21+50 and 26.25+62.5 g/ha can be attributed to effective weed control. These treatments effectively reduced weed competition, allowing the rice plants to have better access to these resources with sustained weed control throughout the growing season, minimizing nutrient losses to weeds and maximizing the availability of nutrients for the rice crop. The improved nutrient absorption and utilization by rice lead to enhanced rice growth and higher nutrient uptake.

Conclusion

It may be concluded that pyrazosulfuron + oxaziclomefone 21+50 g/ha PE resulted in effective control of complex weed flora in transplanted rice with minimal uptake of major (N, P and K) nutrients by weeds and significantly higher uptake of N, P and K by rice and increased rice grain and straw yield.

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RESEARCH ARTICLE

Weed flora dynamics in deep water rice ecosystem of Brahmaputra River ecotone, Assam

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ABSTRACT

Majority of the deep-water rice area along the Brahmaputra Valley in Assam represents typical ecotone zone between the hydrophytic and terrestrial ecosystems, and thus the crop-weed competition environment is different from that of terrestrial land. Keeping this in view, a study was undertaken during 2022 and 2023 in the Brahmaputra ecotone of greater Majuli district of Upper Brahmaputra Valley Agro-climatic zone of Assam. The objective was to study the weed flora composition and weed dynamics in deep water rice in the Brahmaputra ecotone in different land situations. The study was conducted by random plotting of one square meter quadrats in the areas along the river in three distinct situations, *viz,* i. Temporary River Island (TRI) of *Dhodang chapori*, ii. Permanent River Island (PRI) and iii. Permanent River edge (PRE) of *Dhodang- Ujjirati*. The climate of the study area is subtropical with a hot-humid summer, heavily showered monsoon and a mild-moderate winter. The soil nutrient content was moderately rich. Sixty weed species were observed during entire cropping period of this study in TRI, out of which 10 species were invariably present from crop growth stage (CGS) 1 to 3. In PRI and PRE, 67 and 49 weed species, respectively, were observed. *Cynodon dactylon* was found to be the most successful weed species and was dominant in the fields from pre- to post monsoon situations and it showed very strong association with *Arundo donax.* In temporary islands, no strong weed-species association was detected. However, in permanent edge ecotone zone, *Cyperus difformis* had strong negative association with *Eleocharis geniculata* and *Cynodon dactylon,* followed by *Alternanthera philoxeroides.* The permanent river islands and temporary islands were dominated by grasses, whereas sedges were dominant in permanent edges. The number of species and weed biomass revealed very strong correlation with Margalef's species richness index, Pielou's evenness index and Shannon and Wiener's diversity index. However, the correlations of all the diversity indices with soil pH, available N, P and K, were found to be weak to very weak. The results of weed flora association study reflected the increasing community relatedness as TRI> PRE > PRI, which might be due to the presence of least disturbance in soil, cropping, and resource availability in permanent islands in comparison to other land situations.

Keywords: Assam, Deep water rice, Brahmaputra, Ecotone, Weed flora, Weed dynamics, Weed diversity indices

INTRODUCTION

Weeds are comparatively fast-growing plants, highly competitive and highly capable of changing floristic composition of a place, and thus, the pattern of biodiversity. Hence, the species appeared, their dominance spectrum, biomass accumulated in definite time frame, association pattern, etc. are always been considered as some of the important parameters in the study of crop weed competition, as well as in floristic analysis, which are rather important in vegetation study of fragile soils or river beds which are very susceptible to erosion and other disturbances caused by water, wind and human activities. The Middle Brahmaputra floodplains of Assam encompass an area of 7294.85 km^2 (Bhuyan *et al*. 2024). Being one of the largest braided rivers in global scenario, the mighty river Brahmaputra possessed nearly 3.60 lakhs hectares of land (as per Socio Economic Survey 2002-03). These river beds, made up of sand-slit deposition, are naturally enriched by annual deposition of humus making suitable for seasonal cultivation of crops. Based on report on National Productivity Council (NPC), several workers (Lahiri-Dutt2014, Momin and Chakraborty 2023) have classified such river beds (vernacular name "*Char*" or "*Chapori*") as (i.) Permanent *Chapori*- that have existed for more than ten years, (ii.) Semi-permanent *Chapories*- those existed from five to ten years and (iii.) Temporary *Chapories*- those existed for less than five years. In some of the *Chapories* suitable for cultivation, farmers used to grow vegetables in dry winter and rice and other

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crops mostly in summer season. Out of different rice cultures practiced in Assam, the deep-water rice is a long duration rice with a crop duration of 5-6 months and was selected for this study, where monsoon floods play a significant role both in growth of rice varieties as well as in changing weed vegetation patterns. The estimated yield reduction due to weed competition in rice varied from 10-80% (Rao and Matsumoto 2017, Rao 2022). The crop yield losses due to weeds depend on several factors such as associated weed flora, weed emergence time, weed density, type of weeds, crops, cropping systems and management practices used (Rao *et al*. 2007, Rao *et al.* 2014). The rice associated weed flora plays several significant roles in ecosystem management, including erosion control.

The deep-water rice locally called as '*Bao Dhan*' in Assam known for its deep-water cultivation grown in flooded conditions with water more than 50 cm deep for at least a month (Catling *et al.*1992, Rohila *et al.* 2019). In global scenario, deep water rice varieties contribute approximately 10% of the total rice production, even though their yields are low, they support 100 million people who live in areas which get flooded extensively every year during the rainy season, such as in the great river deltas in south and southeast Asia (Sauter 2000). Deep water rice is also known for its high nutritional value. The red colour of rice is conferred by the anthocyanin pigments, and it is known for its high medicinal value (Maibangsa *et al.* 2023). Unlike other rice varieties, deep water rice is characterized by its ability to sustain growth in deep water and survive in flooded environment by exposing leaves above the water surface through elongation of the internodes to maintain respiration and photosynthesis. The Ganges-Brahmaputra-Meghna Basin, Nepal and several minor areas in Assam, account for 58 % of Asia's deepwater rice and 55 % of the world's total deepwater rice (Tandon and Soni 2020). Among the states of India, Assam accounts for the highest percent (20%) of deep water rice cultivation, which is approximately 100,000 hectares of area. Most of the deep water rice area in Assam is located in Dhemaji, Lakhimpur, Sivasagar, Jorhat and Majuli districts of Upper Brahmaputra Valley, Kamrup, Nalbari, Barpeta and Goalpara districts of Lower Brahmaputra valley and Morigaon district of Central Brahmaputra Valley agro-climatic zones of the state.

Majority of area where deep water rice is cultivated along the Brahmaputra Valley in Assam represents typical ecotone zone between the hydrophytic and terrestrial ecosystems. Thus, the crop-weed competition environment in Brahmaputra Valley is different from that of terrestrial land, where weed flora played a significant role in crop productivity under the naturally enriched fertile soil, extremely shallow water table and often treeless windy and sunny environment (Borah *et al.* 2024). It is important to understand the weed flora dynamics for developing better weed management technologies. Hence, this study was undertaken during 2022-2023 in the Brahmaputra ecotone of greater Majuli district of Upper Brahmaputra Valley agro-climatic zone of Assam with an objective to study the weed flora composition and weed dynamics in deep water rice in the Brahmaputra ecotone in different land situations.

MATERIALS AND METHODS

Study site: The study was confined to three distinct ecosystems, which have been classified based on Momin and Chakraborty (2023) as follows:

1) Temporary river islands (TRI), at *Dhodang chapori* (Latitude-26°44′57″N, Longitude-94°10′ 54″E) which were islands separated from the river banks by a perennial channel and existed for less than five years.
2) Permanent river island (PRI), at *Sikoli chapori* (Latitude-26°54′34″ N, Longitude-93°58′14″E)- The long duration river beds (existed for more than ten year) separated from river banks by three perennial channels and
(3) Permanent river edge (PRE), at *Dhodang Ujjirati*, (Latitude-26°47′26″N, Longitude-93°59′15″E)- The river beds situated adjacent to the banks of river Brahmaputra, the age of which was more than ten years.

The study area, being a part of the Upper Brahmaputra Valley Agro-climatic zone of Assam, has experienced subtropical monsoon climate, with a hot and humid summer, heavily showered monsoon and a mild and moderate winter. The atmospheric temperature varied from 6° to 36°C, the average annual rainfall ranges from 202 to 210 centimetres and average annual relative humidity varies from 78 to 80%.

The physico–chemical properties of the soils of PRI, TRI and PRE were evaluated at the Assam Agricultural University (**Table 1**).

Data collection: The observations in deep water rice fields were started since 2022, and farmers were interviewed regarding associated weed problem and management strategies adopted. Weed data was collected for the present analysis both in 2022 and

Table 1. Physico-chemical properties of soils of deep-water rice fields along Brahmaputra River ecotone in 2023

	Soil P^H	Electrical Conductivity (ds/m)	Organic Carbon (%)	Available Nitrogen kg/ha	Available Phosphorus kg/ha	Available Potassium kg/ha	Texture
PRI	5.15	0.1	0.73	273.7	23.94	328.18	Silt loam
TRI	5.5 to 6.8	0.11	0.57	236.38	23.76	188.55	Highly Variable silty to Sandy loam
PRE	4.88	0.1	0.7	290.22	24.52	198.27	Silt loam

PRI= Permanent River islands; TRI= Temporary River islands; PRE= Permanent River edges

2023 from the selected riverbeds. For collection of data, 1 m x 1 m square quadrats were used. Altogether 10 quadrats were plotted randomly within a radius of 20m from the GPS point recorded in each crop growth stage (CGS) in each land situation. The distribution of CGS were as follows: CGS-I: Before the monsoon flood, in between 30-50 days after sowing (DAS); CGS-II: During the monsoon flood, nearly at 110 to 130 DAS, and CGS-III: After receding the monsoon flood, nearly at 150 to 170 DAS. Collected weeds were immediately sorted out species-wise and their density was recorded by counting. Considering runners as propagating organ, rooted slips of perennial species were considered as separate individuals in the counting process. Basal diameter of each species was recorded nearly at ground level. Collected weeds were oven dried at around 65°C for recording the weed dry weight (biomass). Identification of weed species was authenticated in the "Weed herbarium" of Assam Agriculture University, Jorhat.

Floristic composition: In determining floristic composition of weed flora, following formulae were used as described by Githae *et al.* (2007) and Akwee *et al.* (2010):

(i) Basal area (BA) and relative dominance:

Basal area of species in each quadrat =Average BA x number of Individuals, where: Average BA= $\pi d^2/4$; d= Average basal diameter of the weed; and

Relative Dominance (Rdom)(%)= ΣBA_i x 100 / ΣBA_n

(ii) Density, abundance and relative density:

Density (D) = Number of individuals of each species / Total number of quadrats plotted; and Relative density (RD) (%) = ΣD_i x 100/ΣD_n

(iii) Frequency and relative frequency:

Frequency (F) (%)= Number of quadrats where the species occurred x 100 / Total number of quadrats plotted; and Relative Frequency (RF) (%) = ΣF_i x 100 /ΣF_n

(iv) Importance value index (IVI) and Sum dominance ratio (SDR): The IVI was computed by summing up RD, RF and ground space occupied (Rdom) by each species. The sum dominance ratio (SDR) is the percent values of IVI.

IVI = RD + RF + Rdom and SDR = IVI / 3

Community relationship: For determination of diversity, similarity-dissimilarity, etc. amongst the weed communities of different locations, following formulae were used:

(v) Shannon and Weiner diversity index (H) (Shannon and Weaver 1949):

H = -ΣPi*(LNPi), where: Pi= Proportion of Individuals of the community and

LN= Natural logarithm.

(vi) Pielou's evenness index (I) (Pielou 1977): I = H/H_{max} where, H= Number derived from Shannon's diversity index, H_{max} = (-) Σ1/S*LN(1/S) and S= Total number of species.

(vii) Species richness index (Dmg) (Margalef 1951): Dmg= (S-1) / LN(N)

Where, S= Number of species; N= Total number of individuals in the community.

(viii) Simpson's Diversity Index (SDI) (Simpson 1949):

SDI = 1 – {Σn*(n-1) / N*(N-1)}

Where, n = Total number of individuals of a particular species and

N = Total number of individuals of all species

Inter specific association: The association between two species and coupling coefficient (AC) was determined by identifying the nearest neighbour to each individual and for that the species with SDR value above 9.0 were selected. By avoiding the highly disturb crop growth period during monsoon flood (CGS-2), the unit-area (quadrat) of CGS-1 and CGS-3 of each location were taken into account. The presence and absence of any two species (A and B) were counted and the number of samples containing both (a), only species A (b), only species B (c) and neither A and B(d) were recorded. AC values were calculated as follows (Gu *et al.* 2017, Ma *et al.* 2022, and Juan *et al.* 2023).

If $ad < bc$ and $c < b$, then $AC = ad\text{-}bc/(a+b)(b+d)$

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If $ad < bc$ and $a < d$, then $AC = ad\text{-}bc/(a+b)(a+c)$, and

If $ad < bc$ and $a > d$, then $AC = ad\text{-}bc/(b+d)(c+d)$.

Where, AC values range from -1 to +1. When AC=0.67, a strong positive connection exists; $0.67 > AC > 0$ indicates a weak positive connection. AC = 0 indicates no connection, the species are completely independent, and $-0.67 < AC < 0$ indicates a strong negative connection.

RESULTS AND DISCUSSION

Species composition

TRI- *Dhodang Chapori*: In the temporary river islands of *Dhodang Chapori*, a total of 14 weed species were recorded at CGS-1 of deep-water rice during the study. Poaceae was the largest family with 6 weed species. Malvaceae was the second largest family with two weed species. Other six families had one weed species each. Out of total fourteen weeds recorded at CGS-1, five were dicots and nine monocots including two broad-leaved monocots, six grasses and one sedge. Thirteen weed species were recorded at CGS-2, where too Poaceae was the largest family with all six weeds that were previously observed. It was observed that *Panicum repens*, which was prevalent in CGS-1 could not survive in deep water condition (85-100cm). On the other hand, *Paspalum distichum* appeared later and successfully survived during deep water condition along with other previously occurred grassy species.

Six weeds were recorded at CGS-3, where too Poaceae retained as the largest family with fifteen weed species. Cyperaceae was the second largest family with 6 species and Amaranthaceae and Asteraceae were the third largest families with four species each. Out of total sixty weeds recorded at CGS-3, four were Pteridophytes, twenty-nine were dicots and twenty-seven monocots, including six broad-leaved monocots, fifteen grasses and six sedges.

Sixty weed species were observed during the entire cropping period out of which 10 species were invariably occurred in all the crop growth stages, *viz. Alternanthera philoxeroides*, *Colocasia esculenta, Cynodon dactylon, Cyperus haspan, Echinochloa colona, Hymenechne amplexicaulis, Ipomoea carnea, Leersia hexandra, Paspalum notatum* and *Sagittaria guayanensis*. Few species, namely *Bombax ceiba, Panicum repens* and *Parthenium hysterophorus* could not survive during flooded situation and hence did not appear during CGS-2, but these weed species reappeared in the CGS-3. The increasing flood water as well as competitive ability of crop might have restricted their growth during CGS-2.

Three weed species, namely *Ageratum houstonianum*, *Marsilea minuta* and *Paspalum distichum* occurred in CGS-2, and continued till harvest of rice. Unstable ponded water in the sandy-silty riverbeds was the characteristic feature in the study area, even during the monsoon flood. That might encourage the emergence and growth of such weed species, which can withstand short flooding period, especially in sandy situation.

As many as 43 weed species occurred at CGS-3, including, 3 Pteridophyte, 8 grassy species, 5 sedges, 23 broad-leaved dicots (BLWS) and 4 broad-leaved monocots. Probably the propagules of those weeds were disseminated to the site by flood water, which got emerged and established after receding of ponded water at CGS-3.

Site-2: PRI-*Sikoli Chapori*: *Sikoli Chapori* representing permanent river islands, deep water rice fields of which are annually inundated during monsoon flood. Here, twenty-one weed species, belonging to ten families were recorded at CGS-1. Seven weeds were of Poaceae, four were of Asteraceae two each species were of Cyperaceae and Onagraceae. Other six weeds were of Amaranthaceae, Fabaceae, Linderniaceae, Lythraceae, Phyllanthaceae and Verbenaceae, with one species each.

Out of total twenty-one weeds recorded in CGS-1 at PRI, twelve were dicots and nine monocots including seven grasses and two sedges. Sixty-seven weed species were recorded at CGS-3 after receding of monsoon flood. Poaceae again was the largest family with seventeen species. Six species each were of Asteraceae and Cyperaceae family. Three weed species each were of Amaranthaceae and Onagraceae. Apiaceae, Commelinaceae and Phyllanthaceae families were represented by two species each.

Out of total sixty-seven weeds recorded at CGS-3, three were Pteridophytes [*Ceratopteris thalictroides, Equisetum hyemale* and *Marsilea minuta*], thirty-six dicots and twenty-eight monocots including four broad-leaved monocots, six sedges and eighteen grasses (seventeen belonging to Poaceae family and one to Typhaceae).

Out of sixty-nine weed species recorded in the cropping period, *Acmella ciliata, Alternanthera philoxeroides, Arundo donax, Cynodon dactylon,* *Cyperus difformis, Echinochloa colona, Eclipta prostrata, Fimbristylis littoralis, Hymenechne amplexicaulis, Lindernarnia anagalis, Phyla nodiflora, Ludwigia decurrans, L. hyssopifolia, Parthenium hysterophorus, Paspalum conjugatum, P. distichum, P. notatum, Phyllanthus virgatus* and *Rotala macrandra* occurred throughout from CGS 1 to CGS-3.

Site-3: PRE-*Dhodang-Ujjirati*: In *Dhodang-Ujjirati*, deep water rice was cultivated in the permanent Chapories adjacent to the mainland of Majuli (PRE). In such a situation, twenty four weed species were recorded during 30-50 DAS. Poaceae family was represented by 7species; Cyperaceae with five species and 12 families, *viz*. Alismataceae, Araceae, Commelinaceae, Amaranthaceae, Asteraceae, Convolvulaceae, Euphorbiaceae, Linderniaceae, Lythraceae, Marsileaceae and Pteridaceae, with one species each.

Fourteen weed species were recorded at CGS-2 during the flood. In deep water condition, fourteen weed species were recorded, where Cyperaceae appeared was the most dominant family and Poaceae was the 2nd largest family. One weed species each belonged to five families, *viz*. Alismataceae, Commelinaceae, Linderniaceae, Lythraceae and Onagraceae. Out of total fourteen weeds recorded at CGS-2, three were dicots and eleven were monocots including two broad-leaved monocots, three grasses and six sedges.

Forty-seven weed species, belonging to twenty-four families, have been recorded during 160-180 DAS (CGS-3) in the sandy edges, at the post flood situation. Poaceae(11), Cyperaceae (7) and Asteraceae (4), Alismataceae (1), Amaranthaceae (1), Apiaceae (1) and Onagraceae (1) were the families of weed species that occurred at CGS-3. Other 16 families were represented at this stage with one species each. Three Pteridophytes, twenty-two dicots and twenty-two monocots including four broad-leaved monocots, eleven grasses and seven sedges were recorded at CGS-3.

Out of forty-nine weed species recorded in the cropping period, eleven weed species, *viz. Commelina diffusa, Cynodon dactylon, Cyperus difformis, C. haspan, C. iria, C. rotundus, Echinochloa colona, Fimbristylis littoralis, Lindernia anagallis, Ludwigia hyssopifolia, Paspalum distichum* and *Rotala indica* successfully survived in all the three crop growth stages. Twelve species namely, *Ageratum houstonianum, Alternanthera philoxeroides, Ceratopteris thalictroides, Colocasia esculenta, Cyperus rotundus, Eleucine indica, Euphorbia hirta, Hymenachne amplexicaulis, Leersia hexandra, Marsilea minuta, Paspalum notatum* and *Sagittaria guayanensis* could not survive during flooded situation and hence did not appear during CGS-2 but reappeared in the CGS-3, except *Hymenachne amplexicaulis* and *Leersia hexandra*. The increasing flood water as well as competitive ability of crop might have restricted their growth during the CGS-2. Two weed species, namely *Butomopsis latifolia* and *Kyllinga brevifolia* appeared in the CGS-2 and continued upto CGS-3.

Dominance spectrum

The dominance spectrum of weed flora was determined as per the IVI or SDR values. The most dominant weed species with SDR value above four in either of the crop growth stages have been short listed in the **Table 2** showing their relative density and relative frequency. Grasses were rather dominant in island ecosystems rather than permanent edges, in PRE situations, sedges became dominant during and after flood conditions.

This study revealed that *Cynodon dactylon* was the most successful weed with the highest Relative Density (RD) throughout the cropping periods in deep water rice and withstands the flooding period with the relatively highest density in TRI. Non-persistence of flood water for a longer period and adaptability of the weed in short day flooding could be the reason of survival of *Cynodon dactylon* in deep water rice of TRI despite of flooding periods during the monsoon season. *Cynodon dactylon* recorded the highest SDR value in before (53) and post flood situations (16) and second highest (19) during flood situation in the study area. The most dominant weed during flood was *Leersia hexandra*. The cumulative SDR value of grasses was 70.4 , 63.6 and 64.1 in CGS-1, 2 and 3, respectively, followed by the broad-leaved dicots with 20.1, 18.9 and 19.1, respectively.

In PRE ecosystems, *Cyperus difformis* was the most dominant weed in CGS-1, closely followed by *Cynodon dactylon*, while late-emerged *Eleocharis geniculata* dominated the field in later stages. The cumulative SDR of grasses in TRI ecosystems remained above 63 in the entire period of cropping and was as high as 70.4 at CGS-1. Similarly, the SDR of grasses varied from 73.5 at CGS-1 to 58.4 at CGS-3 in the permanent river islands. In both the situations, the cumulative SDR of sedges were rather lower than BLWs. In PRI ecosystems, *Paspalum distichum* and *Cynodon dactylon* were the most dominant weeds in CGS-1, while, *Cynodon dactylon* and *Arundo donax* in CGS-3. The robust grass *Arundo donax* was found as an important constituent of river ecotone wild vegetation and appeared as facultative weed of deep water rice rather prominently in PRI ecosystems.

The cumulative SDR of grasses was as high as 45.0 followed by that of BLWs (36.7) at CGS-1 in PRE, whereas, that of sedges was 85.1 and 47.9 in CGS-2 and CGS-3, respectively. At PRE, at species level, however, the grassy weeds *Cynodon dactylon* (CGS-1, 2 and 3), *Leersia hexandra* (CGS-2) and *Eleucine indica* (CGS-3) were the most dominant over other associated weed species.

Diversity Indices

The diversity of species in the community of different times in different location has shown two distinct trends between islands and edges. Both in temporary river islands as well as permanent river islands, the Shannon and Wiener Diversity Index has shown an increasing trend corresponding to the crop growth stages. On the other hand, in PRE the diversity index was the highest (2.470) at pre-monsoon period, declined to 1.047 during monsoon flood, and again rose to the extent of 2.297 at post flood period. This finding indicated the role of monsoon flood in controlling weed population rather effectively in the permanent edge situation. Instability of monsoon flood in the islands might be least destructive which was reflected in survival of several weed populations appeared in the field in the pre monsoon period, as well as reappearance of some species at post monsoon period after temporary suppression during flooding period. Simpson's Diversity Index (SDI) has shown similar trend for the weed population of PRI and PRE. However, SDI has shown a slight declination during monsoon and little rise at post monsoon period from 1.0 to 0.85 representing the influence of monsoon flood in controlling the population of certain weed species.

Margalef's index ('Dmg') value indicated the species richness or diversity, considering the total number of individuals observed (Kitikidou *et al*. 2024). In PRI, Dmg varies from 3.387 to 12.976 and in TRI 3.782 to 11.757, whereas, in PRE it varied from 5.119 to 9.711 at CGS-1 and CGS-3, respectively. In all the cases the index was decreased during monsoon flood corresponding to declining

Table 2. Relative density (RD), relative frequency (RF) and sum dominance ratio (SDR) of weed groups and most dominant weed species in deep-water rice at different crop growth stages in different land situations along Brahmaputra River ecotone in 2022 and 2023

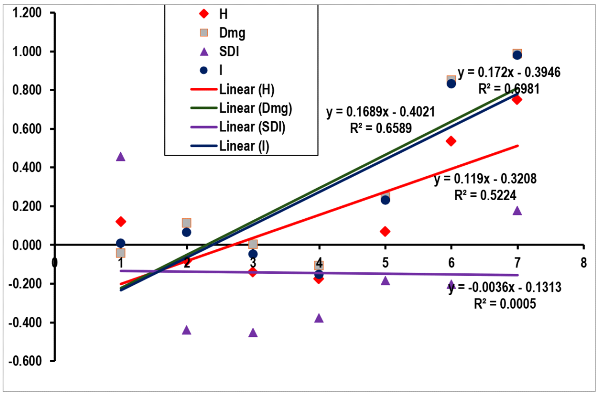
Dominat weed species	CGS-1			CGS-2			CGS-3		
	RD	RF	SDR	RD	RF	SDR	RD	RF	SDR
TRI: *Dhodang chapori*									
Alternanthera philoxeroides (Mart.) Griseb	5.47	12.5	7.46	16.27	13.11	**13.31**	4.23	3.14	3.4
Cynodon dactylon (L.) Pers.	**66.24**	**20.83**	**53.05**	30.45	9.84	**18.9**	24.73	10.47	**16.25**
Eleusine indica (L.) Gaertn.							9.79	5.24	**14.18**
Leersia hexandra Sw.	3.22	4.17	3.37	11.71	14.75	**23.26**	1.49	3.66	2.02
Total BLWs	17.36	45.83	26.65	25.96	37.71	26.51	19.11	43.98	22.69
Total Grasses	79.42	50.00	70.38	63.63	50.83	63.64	66.15	45.55	64.14
Total Sedges	3.22	4.17	2.97	10.41	11.48	9.86	14.74	1047	13.17
PRE: *Dhodang-Ujjirati*									
Cynodon dactylon (L.) Pers.	**22.38**	**8.14**	**13.65**	5.4	5.40	6.17	27.41	12.68	**15.45**
Cyperus difformis L.	16.48	5.81	**14.97**				0.39	1.41	0.6
Cyperus haspan L.	0.51	2.33	0.95	15.37	10.14	**10.89**	1.75	4.23	2.07
Eleocharis geniculata (L.) Roem				71.01	13.04	**58.83**	34.01	4.23	**41.7**
Leersia hexandra Sw.	**8.44**	4.65	**11.32**				1.17	1.41	0.92
Paspalum notatum Flugge	**10.38**	6.98	**11.78**				5.25	2.82	3.38
Total BLWs	31.03	54.66	36.72	2.29	24.64	8.99	14.38	45.12	**20.12**
Total Grasses	49.86	32.56	45.03	3.14	14.49	5.94	46.18	38.06	**31.93**
Total Sedges	19.12	12.79	18.24	94.56	60.86	85.08	39.45	16.92	**47.93**
PRI: *Sikoli chapori*									
Arundo donax L.	8.15	7.94	**12.21**				4.61	0.90	**10.81**
Cynodon dactylon (L.) Pers.	44.83	14.29	**27.36**				38.32	9.91	**25.74**
Eleusine indica (L.) Gaertn.							5.85	2.70	9.26
Paspalum distichum L.	22.19	12.7	**28.5**				0.54	1.80	0.8
Total BLWs	15.64	39.68	19.8				27.14	55.86	31.55
Total Grasses	79.84	46.03	73.52				60.15	35.13	58.36
Total Sedges	4.51	14.28	6.69				12.64	9.01	10.06

diversity triggered by flood. Pielou's index ('I') is used to measure how evenly the species were distributed in a community. In CGS-1 the Pielou's index of weed flora was as high as 18.651 in PRE ecosystem, which was nearly 52% higher than PRI and 147.8% higher than that of TRI ecosystems. However, Pielou's index was of the trend of TRI>PRI>PRE at CGS-3 (**Table 3**).

The number of species and weed biomass revealed very strong correlation with Margalef's species richness index, Pielou's evenness index and Shannon and Wiener's diversity index. However, the correlations of all the diversity indices with soil pH, available N, P and K, were found to be weak to very weak (**Table 3, Figure 1**).

Inter-specific association

Species interactions are of central importance in the ecology of a species (Sanjerehei and Rundel 2020). In the present study, inter-specific associations amongst neighbouring weeds (tested for dominant weeds only with SDR value above 9.0) revealed a few strong associations with coupling value (AC) 1.0 (both +ve and -ve) and majority of associations were weak to very weak (**Table 4**). A very strong positive AC value was recorded between *Arundo donax* and *Cynodon dactylon*, in the PRI at *Sikoli chapori* followed by *A. donax* x *Paspalum distichum* (0.3) indicating the similarity in the requirements between the species of each pair. In contrary, in the same location, *Eleucine indica* revealed very strong negative association (AC= -1.0) with *Arundo donax* and *Paspalum distichum*. Negative association between species may occur because species have different resource requirements; resources compete and are used exclusively by species, and interference between



H: Shannon and Wiener diversity index; Dmg: Margalef's species richness index; SDI: Simpson's Diversity index and I: Pielou's evenness index

1. Soil pH; 2. Organic Carbon; 3. Available Nitrogen; 4. Available Phosphorus;

5. Available Potassium; 6. Weed biomass; 7. Number of Species

Figure 1. Correlations among different indices of weeds in deep water rice ecosystems of the Brahmaputra River ecotone

Table 3. Different diversity indices in deep water rice weeds in different land situations during 2022 and 2023 and their correlation with the species richness, weed biomass and soil characteristics

	Total number of weed species (S)	Weed biomass (g/m^2)	Shannon and wiener diversity index (H)	Margalef's species richness index (Dmg)	Simpson's diversity index (SDI)	Pielou's evenness index (I)
PRI CGS-1	21	156.73	1.775	3.387	0.735	12.242
PRI CGS-2	67	399.264	2.531	12.976	0.828	40.332
TRI CGS-1	14	17.917	1.419	3.782	0.997	7.527
TRI CGS-2	13	51.483	2.13	2.383	0.847	10.797
TRI CGS-3	60	335.411	2.898	11.757	0.907	42.47
PRE CGS-1	24	157.457	2.47	5.119	1	18.651
PRE CGS-2	14	214.702	1.047	1.799	0.468	5.553
PRE CGS-3	46	360.294	2.297	9.711	0.807	27.595
Correlation between			H	Dmg	SDI	I
Soil pH			0.121	-0.043	0.457	0.009
Organic Carbon			-0.079	0.113	-0.438	0.064
Available Nitrogen			-0.140	0.004	-0.452	-0.048
Available Phosphorus			-0.174	-0.108	-0.378	-0.153
Available Potassium			0.070	0.249	-0.183	0.232
WEED biomass			0.537	0.851	-0.203	0.832
Number of Species			0.751	0.988	0.177	0.980

PRI= Permanent River islands; TRI= Temporary River islands; PRE= Permanent River edges; CGS- crop growth stages species produces occasional exclusion (Chesson 2000, Ludwig *et al.* 1988). In the deep water rice of TRI at *Dhodang chapori* no strong weed-species association occurred. Frequent changing of weed flora composition caused mostly for flooding and water current, and under the influence of several biological agents, including human interference might be the reasons behind the unstable coupling behaviour in these temporary islands.

In permanent edge (PRE) ecotone zone, *Cyperus difformis* had strong negative association with *Eleocharis geniculata* and *Cynodon dactylon* with (-)1.0 coupling value followed by *Alternanthera philoxeroides* x *Cynodon dactylon* (AC= -0.618) and rest of the weed pairs had very low coupling values. It is fact that community relatedness reflects the stability of the community structure (Juan *et al*. 2023). When a community is in the early stage of succession, the overall degree of community relatedness is low, and negative association may even occur (Liu *et al*. 2017); however, the overall community relatedness tends to be higher in course of achieving stable co-existence in course of succession of a community. The results of weed flora association study, thus, reflected the increasing community relatedness as TRI> PRE >PRI, which might be due to the presence of least disturbance in soil, cropping, and resource availability in permanent islands in comparison to other land situations.

Table 4. Inter-specific association and coupling coefficient (AC) between dominant weed species of deep-water rice in different land situations along Brahmaputra River ecotone in 2022 and 2023

Species A	Species B	AC
PRI: *Sikoli Chapori*		
Arundo donax	*Eleusine indica*	-1.000
Arundo donax	*Paspalum distichum*	0.333
Arundo donax	*Cynodon dactylon*	1.000
Eleusine indica	*Paspalum distichum*	-1.000
Eleusine indica	*Cynodon dactylon*	0.029
Paspalum distichum	*Cynodon dactylon*	0.057
TRI: *Dhodang Chapori*		
Alternanthera philoxeroides	*Leersia hexandra*	0.242
Alternanthera philoxeroides	*Eleusine indica*	-0.333
Alternanthera philoxeroides	*Eragrostis Unioloides*	0.000
Alternanthera philoxeroides	*Cynodon dactylon*	-0.143
Leersia hexandra	*Eleusine indica*	0.318
Leersia hexandra	*Eragrostis Unioloides*	0.045
Leersia hexandra	*Cynodon dactylon*	0.018
Eleusine indica	*Eragrostis Unioloides*	-0.100
Eleusine indica	*Cynodon dactylon*	-0.500
Eragrostis Unioloides	*Cynodon dactylon*	0.100
PRE: *Dhodang Ujjirati*		
Paspalum notatum	*Alternanthera philoxeroides*	0.354
Paspalum notatum	*Leersia hexandra*	0.016
Paspalum notatum	*Cyperus difformis*	0.300
Paspalum notatum	*Eleocharis geniculata*	-0.125
Paspalum notatum	*Cynodon dactylon*	-0.354
Alternanthera philoxeroides	*Leersia hexandra*	0.213
Alternanthera philoxeroides	*Cyperus difformis*	0.300
Alternanthera philoxeroides	*Eleocharis geniculata*	-0.300
Alternanthera philoxeroides	*Cynodon dactylon*	-0.618
Leersia hexandra	*Cyperus difformis*	0.344
Leersia hexandra	*Eleocharis geniculata*	0.067
Leersia hexandra	*Cynodon dactylon*	-0.213
Cyperus difformis	*Eleocharis geniculata*	-1.000
Cyperus difformis	*Cynodon dactylon*	-1.000
Eleocharis geniculata	*Cynodon dactylon*	0.052

In deep water rice, especially in Brahmaputra River ecotone, farmers are dependent on flood for weed management and growth and yield of the crop as well. Better understanding of weed dynamics and crop weed association at different crop growth stages in different land situations might be the key factor for adoption of effective and eco-friendly agronomic management practices to manage the weeds.

Conclusion

The deepwater rice fields along the Brahmaputra River ecotone possessed some unique-features in crop-weed association during its 5 to 6 months long cropping period, between March to November. Monsoon flood caused mortality of most of the early emerged weeds and certain other weeds carried by water current were added. The number of species and weed biomass revealed very strong correlation with Margalef's species richness index, Pielou's evenness index and Shannon and Wiener's diversity index. However, the correlations of all the diversity indices with soil pH, available N, P and K, were found to be weak to very weak.

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RESEARCH ARTICLE

Bio-efficacy of carfentrazone-ethyl against broad-leaved weeds and its effect on direct-seeded rice productivity and nutrient uptake

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ABSTRACT

Farmers are preferring direct-seeded rice (DSR) than traditional transplanted rice cultivation practices due to water scarcity and agricultural labors shortage. However, weeds are a major challenge in DSR production systems. A field experiment was conducted at the Research farm of Bidhan Chandra Krishi Vishwavidyalaya, West Bengal, India ((22°97' N, 88°44' E, and 9.75 m above MSL) during *Kharif* seasons of 2022 and 2023 to evaluate the efficacy of varying doses of carfentrazone-ethyl in comparison with oxyfluorfen and hand weeding on diversified weed flora and assess their effect on growth, nutrient uptake and yield of direct-seeded rice for identifying a suitable herbicide and its optimum dose for sustainable direct-seeded rice production. There were seven treatments, *viz.* four doses of carfentrazone-ethyl 40% DF (carfentrazone-ethyl) 15, 20, 25 and 30 g/ha; oxyfluorfen 23.5% EC (oxyfluorfen) 240 g/ha; hand weeding twice at 20 and 40 days after seeding (DAS) and weedy check. A randomized complete block design replicated thrice was used. Among the tested herbicides, carfentrazone-ethyl 30 g/ha effectively reduced the total weed density by 55.08% and 53.83% at 30 and 45 days after seeding (DAS), respectively and biomass of broad-leaved weeds and annual sedges by 81.22% and 77.31% at 30 and 45 DAS, respectively, compared to control. The carfentrazone-ethyl 30 g/ha recorded highest rice grain yield too and may be considered as the best treatment for managing weeds, particularly when the broad-leaved weeds and sedges are predominant, in direct-seeded rice.

Keywords: Carfentrazone-ethyl, Direct-seeded rice, Oxyfluorfen, Soil Nutrient uptake, Weed management

INTRODUCTION

Rice (*Oryza sativa* L.) serves as the primary food source for nearly 60% of India's population (Biswas *et al*. 2019), with West Bengal being the leading producer (Directorate of Agriculture 2018, Jambulkar 2023). However, sustaining and enhancing rice productivity remains a challenge, as a 50–60% increase in production will be required by 2025 to meet population-driven demand (Banerjee *et al.* 2018, Rao 2022). The conventional method of rice cultivation involving transplanted rice after puddling is becoming increasingly unsustainable due to its negative impact on soil structure, high water and labour requirements and the formation of hard pans that impede the establishment of subsequent crops (Poddar *et al.* 2014, Rao *et al.* 2017). In addition, the declining groundwater table caused by excessive pumping during peak summer, combined with delayed monsoon onset, further hampers timely transplanting (Lampayan *et al.* 2015). This impacts of rice growth and yield with poor tiller formation, a shortened vegetative period and decrease dry matter accumulation. In this context, direct-seeded rice (DSR) has emerged as a promising alternative, offering advantages such as reduced labour and water use, earlier maturity, mechanization compatibility and enhanced water-use efficiency (Chauhan *et al*. 2012, Yaduraju *et al*. 2021). However, the major constraint in DSR is effective weed management, as the absence of standing water during crop establishment leads to rapid weed emergence and intense crop-weed competition (Singh *et al.* 2009, Rao *et al.* 2020, Rao and Chandrasena 2024). Therefore, a successful weed management in DSR requires a strategic approach considering weed type, land preparation and herbicide efficacy (Rao *et al.* 2007). As manual weeding is time-consuming and costly, herbicide use is a more practical alternative (Jana *et al.* 2020, Yaduraju *et al.* 2021). However, the development and identification of alternative herbicides have become increasingly important to minimize the risk of herbicide-resistant weed biotypes and to maintain high rice yields under direct-seeded conditions. While many pre-emergence herbicides are available in the market for controlling

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weeds, the need for post-emergence herbicide is often realized to combat the weeds emerged during later stages of crop growth (Kundu *et al*. 2020). Carfentrazone-ethyl is a post-emergent, broad-leaved weeds killer, contact, non-residual, translocated herbicide belongs to aryl triazolinone family has been found effective (Shinde *et al*. 2018) by inhibiting activity of protoporphyrinogen oxidase in chlorophyll biosynthetic pathway (Witkowski and Halling 1989). Oxyfluorfen is also a selective post-emergence herbicide that controls weed flora (Poddar *et al*. 2014). This experiment was conducted to evaluate the efficacy of varying doses of carfentrazone-ethyl in comparison with oxyfluorfen and hand weeding on diversified weed flora, and assess their effect on growth, nutrient uptake and yield of direct-seeded rice, for identifying a suitable herbicide and its optimum dose for sustainable direct- seeded rice production in new alluvial zone of West Bengal.

MATERIALS AND METHODS

The field experiment was conducted under subtropical climate during *Kharif* 2022 and 2023 at the research farm of Bidhan Chandra Krishi Vishwavidyalaya ((22°97' N, 88°44' E, and 9.75 m above MSL), West Bengal. The soil was sandy loam containing 53.27% sand, 24.88% silt and 21.85% with a pH of 7.21 and electrical conductivity of 0.18 ds/m. It contained 0.65% organic C, 190.6 kg available N/ha, 20.53 kg available P/ha and 156.3 kg available K/ha. Weekly maximum and minimum temperatures ranged between 29.6 to 36.1°C and 11.9 and 26.9 °C during 2022 and 2023 respectively. Maximum relative humidity ranged from 89 to 94.6% in 2022 and 85.5 to 93.5% in 2023. The annual rainfall during the experimental period was 1450 and 1500 mm in 2022 and 2023, respectively. The experiment was laid out in randomized block design and replicated thrice with each plot area of 25 m^2 (5.0 x 5.0 m). The tested treatments were: carfentrazone-ethyl 40% DF (carfentrazone-ethyl) at 15, 20, 25 and 30 g/ha; oxyfluorfen 23.5% EC (oxyfluorfen) 240 g/ha; weedy check and hand weeding twice at 20 and 40 days after seeding (DAS). The amount of the herbicides was calculated as per treatments on the basis of gross plot area. Herbicides were applied as aqueous solutions at 500 L/ha using a knapsack sprayer fitted with a WFN 040 flood jet nozzle, uniformly across plots as per treatments. Post-emergence application (PoE) of carfentrazone-ethyl was applied at 15 DAS and pre-emergence application (PE) of oxyfluorfen at 3 DAS, as per the treatments dose. Since herbicides efficacy on broad-leaved weeds (BLW) and sedges was being tested, grasses were uprooted whenever they appeared in the experimental plots. Rice (*cv.* IET 4786) seeds were soaked, treated with *Trichoderma viride* (4 g/kg), shade-dried and sown at 20 × 15 cm spacing on 4th and 7th February (2022 and 2023); recommended FYM and fertilizers were applied, crops irrigated as needed and harvested on 4th and 9th June, with grain yield recorded at 15% moisture content.

For collection of data on weed parameters, four permanent quadrats (0.5 × 0.5 m) per plot were used to record weed density and biomass at 30 and 45 days after seeding (DAS); weeds were counted, washed, sun-dried, oven-dried at 70°C for 48 h and weighed. Different weed indices were worked out by using following equations (Banerjee *et al.* 2019, Kundu *et al.* 2020) respectively.

$$WCE = \frac{WDM_C - WDM_T}{WDM_C} \times 100 \ldots\ldots \text{(i)}$$

Where, WCE is weed control efficiency; WDM_c is the weed dry matter weight (g/m^2) in control plot; WDM_T is the weed dry matter weight (g/m^2) in treated plot.

$$Weed\ Infestation = \frac{Total\ number\ of\ weeds\ in\ unit\ area}{Total\ number\ of\ weeds\ and\ crop\ plants\ in\ the\ same\ area} \times 100 \ldots\ldots \text{(ii)}$$

$$TEI = \frac{Y_T - Y_C}{Y_T} \times \frac{WDM_C}{WDM_T} \ldots\ldots \text{(iii)}$$

Where TEI is treatment efficiency index; Y_T is crop yield from the treated plot; Y_C is crop yield from the control plot.

$$WI = \frac{Y_f - Y_t}{Y_f} \times 100 \ldots\ldots \text{(iv)}$$

Where WI is weed index; Y_f is yield from weed free plot; Y_t is yield from treated plot.

$$CRI = \frac{CDM_t}{CDM_c} \times \frac{WDM_c}{WDM_t} \ldots\ldots \text{(v)}$$

Where CRI is crop resistance index; CDM_t is crop dry matter (g/m^2) in treated plot; CDM_c is crop dry matter (g/m^2) in control plot.

$$HI = \frac{Economic\ yield}{Biological\ yield} \ldots\ldots \text{(vi)}$$

Where, HI is harvest index

Initial soil samples were air-dried, sieved (2 mm) and analysed for texture (textural triangle), mechanical composition (hydrometer method), pH and EC (1:2.5 soil: water, Jackson, 1967), available N (hot alkaline $KMnO_4$), P (0.5 M $NaHCO_3$, UV-VIS spectrophotometer) and K (neutral ammonium acetate extraction, flame photometry). Aboveground weed and crop samples were oven-dried (60 ± 5 °C), ground (0.5 mm), acid-digested and analysed for N, P and K content; nutrient uptake was computed on a hectare basis. The benefit-cost ratio (B:C) was calculated by dividing the gross income by the cost of cultivation. All the collected data was subjected to analysis of variance (ANOVA) according to the techniques define for simple randomized complete block design (RCBD) as described by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Weed growth

The experimental plots were infested with diversified weed flora and amongst them broad-leaved weeds (BLW) were the most dominating, followed by sedges and grasses, regardless of the dates of observations. The lowest sedge and broad-leaved weed density and biomass were recorded with hand weeding twice at 20 and 40 DAS, while the highest were observed in the untreated weedy check. Among the herbicides carfentrazone-ethyl 30 g/ha resulted in lowest weed density and biomass of *Ludwigia parviflora* at 30 and 45 DAS, respectively, which was statistically at par with the carfentrazone-ethyl 25 g/ha. The similar trend was observed with other broad-leaved weed species also (**Table 1** and **2**). The same treatment significantly (p≥0.05) reduced the density and biomass of *Cyperus iria* at both 30 and 45 DAS (**Table 1** and **2**). At 30 DAS, the lowest total weed density was recorded with the highest dose of carfentrazone-ethyl, which was statistically similar to the 25 g/ha. At 45 DAS, carfentrazone-ethyl 25 g/ha was significantly superior to all other herbicidal treatments. Furthermore, total weed biomass (broad-leaved weeds and sedges) was markedly reduced with carfentrazone-ethyl at 30 g/ha PoE with a reduction of 81.22% and 77.31% at 30 and 45 DAS, respectively compared to the control. This emphasizes the importance of post-emergence herbicides usage for weed control in direct-seeded rice, as it provides broad spectrum weed control and may safeguards against herbicide resistance. These findings are in conformity with the findings of Shinde *et al.* (2018) who observed lower weed density and biomass with carfentrazone-ethyl compared to other weed management treatments.

Weed control efficiency

Hand weeding twice at 20 and 40 DAT was the most efficient with higher weed control efficiency (**Table 3**) in managing broad-leaved weeds and *Cyperus* spp., at all the growth stages of direct-seeded rice. *Cyperus* spp., a predominant sedge in rice field was most efficiently (> 70%) managed by carfentrazone-ethyl 30 g/ha and was statistically similar with carfentrazone ethyl 25 g/ha. The lowest weed control efficiency was recorded with weedy check as no weed control measures were taken. Carfentrazone-ethyl 15, 20, 25 and 30 g/ha recorded varying levels of efficacy in controlling total broad-leaved weeds. The WCE for total BLW with carfentrazone-ethyl increased with increased dose and carfentrazone-ethyl 30 g/ha dose exhibited the highest efficacy (81.60% at 30 DAS and 70.44% at 45 DAS), which was statistically comparable with

Table 1. Effect of weed management treatments on weed density (no./m²) at 30 and 45 DAS (pooled data of two years) in direct-seeded rice

Treatment	*Ludwigia parviflora*		*Digera arvenses*		*Phyllanthus niruri*		*Spilanthes paniculata*		*Eclipta alba*		*Cyperus* spp.	
	30	45	30	45	30	45	30	45	30	45	30	45
Carfentrazone-ethyl	1.68	2.33	1.60	2.18	1.99	2.25	1.42	1.77	1.97	2.21	2.58	3.19
PoE 15 g/ha	(2.33)	(4.93)	(2.06)	(4.29)	(3.48)	(4.57)	(1.53)	(2.65)	(3.89)	(4.39)	(6.18)	(9.69)
Carfentrazone-ethyl	1.63	2.21	1.57	2.06	1.92	2.13	1.33	1.57	1.82	2.16	2.43	3.09
PoE 20 g/ha	(2.17)	(4.38)	(1.95)	(3.75)	(3.17)	(4.05)	(1.27)	(1.96)	(2.81)	(4.17)	(5.37)	(9.04)
Carfentrazone-ethyl	1.55	2.09	1.46	2.03	1.83	2.09	1.20	1.30	1.74	2.09	2.33	2.93
PoE 25 g/ha	(1.89)	(3.86)	(1.63)	(3.63)	(2.85)	(3.87)	(0.95)	(1.19)	(2.54)	(3.86)	(4.91)	(8.07)
Carfentrazone-ethyl	1.52	2.04	1.44	2.01	1.80	2.01	1.14	1.25	1.72	2.00	2.25	2.91
PoE 30 g/ha	(1.84)	(3.67)	(1.58)	(3.55)	(3.11)	(3.57)	(0.81)	(1.08)	(2.48)	(3.53)	(4.57)	(7.99)
Oxyfluorfen PE 240	2.16	3.26	2.05	2.80	2.40	3.13	1.84	2.41	2.16	3.14	4.47	5.91
g/ha	(4.16)	(10.10)	(3.71)	(7.35)	(5.24)	(9.28)	(2.87)	(5.33)	(4.17)	(9.34)	(19.47)	(34.38)
Control: weedy check	3.13	3.92	2.75	3.55	3.62	3.82	2.50	3.12	3.24	3.85	5.25	6.73
	(9.27)	(14.83)	(7.09)	(12.08)	(12.61)	(14.09)	(5.77)	(9.23)	(10.03)	(14.33)	(27.09)	(44.83)
Hand weeding twice 20	1.20	1.13	1.28	1.23	1.21	1.32	0.94	0.94	1.28	1.45	1.76	1.84
and 40 DAS	(0.95)	(0.78)	(1.13)	(1.01)	(0.97)	(1.24)	(0.39)	(0.39)	(1.15)	(1.61)	(2.61)	(2.87)
LSD (p=0.05)	0.072	0.107	0.066	0.133	0.086	0.090	0.055	0.074	0.079	0.095	0.124	0.158

Values in the parentheses are original value and values outside parentheses are square root transformed {"(X+0.5)} values**;** *DAS = days after seeding; PoE = post-emergence application; PE = pre-emergence application carfentrazone-ethyl 25 g/ha. This indicates a dose-dependent response in controlling broad-leaved weeds as reported by Punia *et al.* (2018) and Singh *et al.* (2013).

Weed indices

The weed infestation index represents the percentage of weeds in the combined population of weeds and crop plants. The treatment efficiency index (TEI) indicates the weed killing potential of a treatment and its phytotoxicity on the crop. Carfentrazone-ethyl 30 g/ha recorded the lowest infestation index (22.17); lowest weed index (6.32) and maximum treatment efficiency (1.48) which demonstrated its superior efficiency against infested weed flora (BLW and annual sedges) in DSR. A similar trend was also observed for crop resistance index. Raj *et al.* (2013) also reported superiority of carfentrazone-ethyl over other herbicides in DSR in terms of different weed indices.

Rice yield and yield attributes

An increase in rice yield of 17.37% to 67.38% over the weedy control was observed with weed management treatments tested (**Table 4**). Among the herbicide treatments, carfentrazone-ethyl 30 g/ha recorded the highest grain yield (3.83 t/ha) which did not differ significantly from weed free (3.95 t/ha), followed by carfentrazone-ethyl 25 g/ha (3.67 t/ha). On the contrary, the minimum grain yield was

Table 2. Effect of weed management treatments on weed biomass (g/m²) at 30 and 45 DAS in direct-seeded rice (pooled data of 2 years)

Treatment	*Ludwigia parviflora*		*Digera arvenses*		*Phyllanthus niruri*		*Spilanthes paniculata*		*Eclipta alba*		*Cyperus* spp.	
	30	45	30	45	30	45	30	45	30	45	30	45
Carfentrazone-ethyl PoE 15 g/ha	1.98	3.68	1.74	4.69	2.47	4.43	1.82	3.58	2.69	4.99	2.84	8.36
Carfentrazone-ethyl PoE 20 g/ha	1.59	3.29	1.55	4.05	1.89	3.75	1.33	2.75	1.95	4.43	2.47	7.99
Carfentrazone-ethyl PoE 25 g/ha	1.47	3.11	1.29	3.87	1.73	2.95	1.21	2.41	1.77	3.81	2.31	7.45
Carfentrazone-ethyl PoE 30 g/ha	1.36	3.08	1.28	3.79	1.72	2.90	1.17	2.35	1.69	3.71	2.23	7.37
Oxyfluorfen PE 240 g/ha	2.33	4.93	2.27	5.47	2.65	5.63	1.74	4.26	3.15	7.53	3.77	10.55
Control: weedy check	7.47	13.97	8.03	15.79	10.41	15.52	4.81	8.29	8.59	16.33	9.59	25.53
Hand weeding twice 20 and 40 DAS	0.116	0.47	0.31	0.53	0.21	0.72	0.10	0.45	0.60	1.55	1.37	2.93
LSD (p=0.05)	0.154	0.287	0.162	0.328	0.213	0.323	0.105	0.182	0.179	0.337	0.197	0.539

*DAS = days after seeding; PoE = post-emergence application; PE = pre-emergence application

Table 3. Effect of weed management treatments on weed control efficiency (WCE), weed infestation index (WII), treatment efficiency index (TEI), weed index (WI), crop resistance index (CRI) in direct-seeded rice (pooled data of 2 years)

Treatment	WCE (%)				WII		TEI	WI	CRI
	Total BLW		*Cyperus* spp.						
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS			
Carfentrazone-ethyl PoE 15 g/ha	65.49	60.10	70.39	66.08	24.84	29.06	0.74	22.11	3.53
Carfentrazone-ethyl PoE 20 g/ha	78.82	65.89	74.24	68.51	22.41	27.99	1.09	14.32	4.14
Carfentrazone-ethyl PoE 25 g/ha	80.96	69.85	75.91	70.82	22.27	25.91	1.44	7.08	4.20
Carfentrazone-ethyl PoE 30 g/ha	81.60	70.44	76.74	71.13	22.17	25.89	1.48	6.32	4.40
Oxyfluorfen PE 240 g/ha	69.06	48.06	60.69	58.68	30.72	37.10	0.36	29.87	2.60
Control: weedy check	0	0	0	0	37.60	42.36	0.00	40.25	1.03
Hand weeding twice 20 and 40 DAS	96.56	93.05	85.71	88.52	17.97	18.43	5.77	0.00	16.09
LSD (p=0.05)	2.68	2.39	2.52	2.40	-	-	-	-	-

*DAS = days after seeding; PoE = post-emergence application; PE = pre-emergence application; BLW = broad-leaved weeds

Table 4. Effect of weed management treatments on direct-seeded rice grain and straw yield and economic analysis (pooled data of 2 years)

Treatment	Yield (t/ha)				Harvest index (%)	Gross returns (₹/ha)	Net returns (₹/ha)	B:C ratio
	Grain			Straw				
	Year I	Year II	Pooled					
Carfentrazone-ethyl PoE 15 g/ha	3.09	3.05	3.07	4.26	41.88	73278	29864	1.69
Carfentrazone-ethyl PoE 20 g/ha	3.30	3.46	3.38	4.65	42.09	80577	37058	1.85
Carfentrazone-ethyl PoE 25 g/ha	3.59	3.75	3.67	5.23	42.27	87943	44199	2.01
Carfentrazone-ethyl PoE 30 g/ha	3.77	3.89	3.83	5.06	42.23	90782	46873	2.07
Oxyfluorfen PE 240 g/ha	2.75	2.79	2.77	3.92	41.40	66308	21939	1.49
Control: weedy check	2.37	2.35	2.36	3.30	41.69	56394	14459	1.34
Hand weeding twice 20 and 40 DAS	3.88	4.02	3.95	5.37	42.38	94005	42230	1.82
LSD (p=0.05)	0.11	0.12	0.12	0.16	-	-	-	-

*DAS = days after seeding; PoE = post-emergence application; PE = pre-emergence application

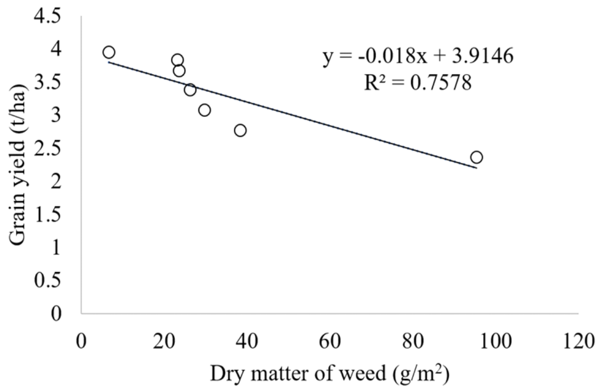

Figure 1. Relationship between weed dry matter accumulation and grain yield

observed with untreated control (2.36 t/ha) with significant DSR yield reduction of 67%. A similar trend was observed for straw yield and harvest index. This indicates that herbicide application significantly improved both grain and straw yields with a marked improvement in the harvest index over the untreated control. The higher yield of rice in effective treatments might be ascribed to effective suppression of weeds during growing phases and also utilization of more resources under lesser weeds condition (Poddar *et al.* 2014). There was a negative correlation (R^2=0.757) have been found between weed dry matter at 45 DAS and rice grain yield (**Figure 1**) indicating that it is essential to control weeds effectively as reported by Shinde *et al.* (2018), Patel *et al.* (2023) and *Singh et al.* (2013).

Nutrient uptake by rice

Plant nutrient uptake by direct-seeded rice was inversely proportional to nutrient uptake by weeds. All weed control treatments recorded significantly higher NPK uptake than weedy check at 45 DAS (**Figure 2**). Hand weeding twice at 20 and 40 DAS and carfentrazone-ethyl 30 g/ha recorded higher NPK uptake by DSR. This could be attributed to better weed control achieved by these treatments. The lowest NPK uptake in the weedy check might be due to intense crop-weed competition as observed by Chakraborti *et al.* (2017).

Nutrient removal by weeds

The uptake of N, P and K by weeds followed the pattern of weed biomass as recorded in different treatments with least in hand weeded twice, while the maximum removal of major nutrients occurred in the weedy check (**Figure 2**). Due to its effective control, carfentrazone-ethyl 30 g/ha resulted in least removal of nitrogen, phosphorus and potassium by weeds (5.58, 1.24 and 5.45 kg/ha respectively) due to its effective control of predominant BLW and sedges confirming Jaiswal *et al.* (2023).

Phytotoxicity of herbicides

The rice plants were carefully examined for phytotoxicity symptoms at 1, 3, 5, 7 and 10 days after herbicide application and no phytotoxicity was observed.

Economics

Among all weed control treatments tested, the highest net return and benefit-cost ratio were recorded with carfentrazone-ethyl 30 g/ha followed by carfentrazone-ethyl 25 g/ha. Although hand weeding improved yields and gross income, the

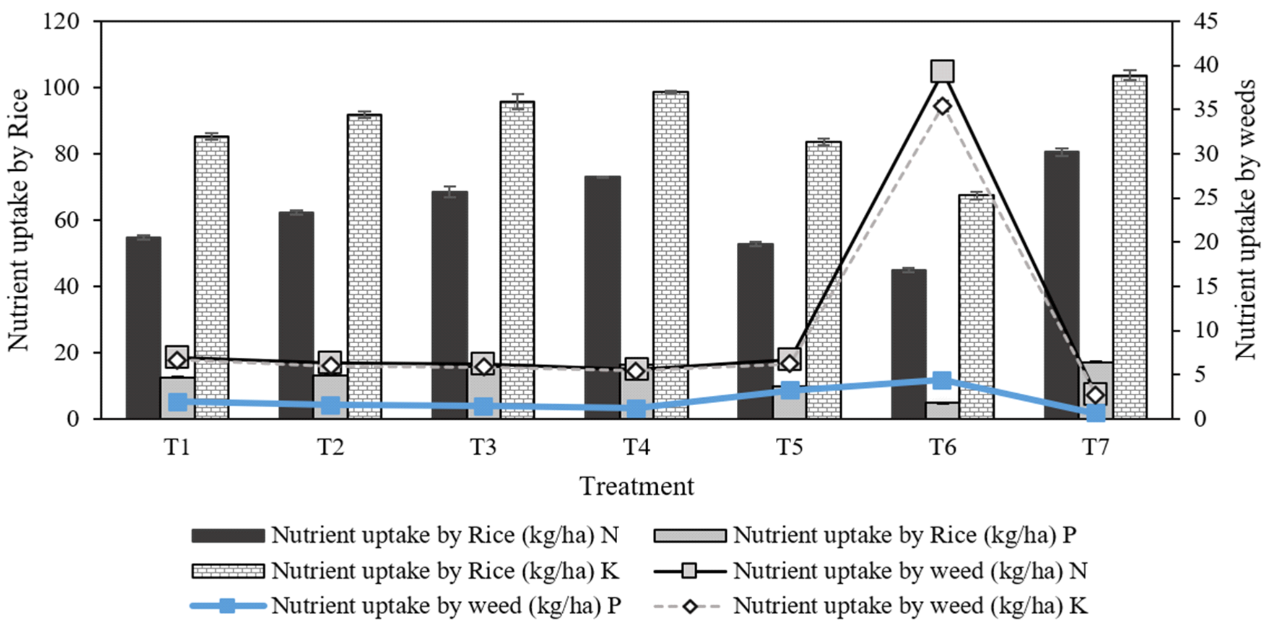

Figure 2. Nutrient uptake (kg/ha) by rice (column) and weeds (line) as affected by weed control treatments at rice harvesting

greater labor requirement and higher labor cost led to reduced benefit-cost ratio indicating that effective herbicide usage is highly efficient, non-laborious and economical than manual weeding.

Based on the findings of this study, it can be concluded that carfentrazone-ethyl 30 g/ha is an effective and safe alternative to the labour-intensive, time-consuming and costly hand weeding practice for controlling broad-leaved weeds and annual sedges predominating direct-seeded rice in the new alluvial zone of West Bengal.

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RESEARCH ARTICLE

Efficacy of pre- and post-emergence herbicides in managing weeds and improving productivity of rice under new alluvial zone

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ABSTRACT

An experiment was conducted during two consecutive *Kharif* seasons of 2020 and 2021 at Kalyani D- Block Research Farm, BCKV, Mohanpur, West Bengal, India. The objective was to study the efficacy of pre- and post-emergence herbicides in managing weeds and improve grain yield of transplanted rice. The dominant grassy weeds in fields were: *Echinochloa colona*, *Cynodon dactylon, Panicum repens;* broad-leaved weeds were: *Ludwigia parviflora*, *Malva neglecta, Eclipta alba* and *Alternanthera philoxeroides* and sedges were: *Cyrus iria and Fimbristylis miliacea*. Pre-emergence application (PE) of pretilachlor 50 % EC (pretilachlor) 0.70 kg/ha followed by (*fb*) passing of conoweeder and sequential application of pretilachlor 0.70 kg/ha PE *fb* post-emergence application (PoE) of bispyribac-Na 10% SC (bispyribac-Na) 25 g/ha were highly effective in providing effective weed control with greater productivity and profitability. The sequential application of pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE provided broad-spectrum weed management, higher crop productivity, and profitability in transplanted rice without any tracible residues in the rice grain and in the soil after harvest.

Keywords: Bispyribac-Na; Conoweeder, Pretilachlor, Productivity, Transplanted rice, Weed management

INTRODUCTION

Rice, a staple food for more than half of the world's population, is grown in more than100 countries with 90% of the total global production from Asia. In India, 44 million hectares (M ha) area is under rice cultivation, with 124 million tonne (MT) production, which shares 21.5% of world rice production (DES 2024). India is largely self-sufficient in rice production, but to sustain self-sufficiency by 2050 and feed a projected population of 1.64 billion people, 197.4 MT of rice will be needed. An additional challenge is that the extra rice will be produced with a lower environmental footprint with limited resources (*i.e.,* land, labour, water, agrochemicals, *etc*.) (Ahmad *et al.* 2021). Biotic and abiotic stresses are a major concern in the modern-day input-intensive agricultural production system as they cause serious economic losses. Among biotic stresses, weeds are major biological constraints and cause a 37% yield loss (Mishra *et al.* 2021). If weeds are not properly controlled, they capture distinctive amount of nutrients, which result in significant loss of yield and economic returns. Weeds were reported to remove approximately 367.8, 220.0 and 291.0% of N, P and K from rice field (Raj and Syriac 2017). Because of weed competition with rice for moisture, nutrients, light and space, about 50.4–80.0% reduction in grain yield was reported (Mahajan and Chauhan 2015, Parthipan and Ravi 2016) with reduced benefit cost ratio by 60.7% (Riaz *et al.* 2018). Puddle-transplanted rice has several advantages, including the retention of a thin layer of water, prevention of percolation losses, the suppression of weeds, and supply of nutrients (Choudhary *et al.* 2021). Rice crop is heavily infested with annual grasses, broad-leaved weeds, and sedges, posing a challenge to weed management (Choudhary and Dixit 2018). Manual weeding is suggested as the best weed management method, but frequent rains, labour shortages, and high labour wages make it challenging, time-consuming, and uneconomical, especially during the critical period of weed competition (Choudhary and Dixit 2018).

Herbicides are an effective alternative weed management strategy at this situation as they require less labour and have the potential to provide useful weed control while reducing labour and production costs (Rao *et al.* 2017). Non-selective herbicides

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have been used prior to crop establishment to control annual and biennial weeds; however, they are less effective for complete weed removal for entire life cycle (Carretta *et al.* 2021). Pre-emergence (PE) herbicides can effectively control weeds during the initial stages of crop growth, while post-emergence (PoE) herbicides are best used for killing the later emerging weeds. Maintaining desired water levels after herbicide application can enhance their efficacy (Kaur *et al.* 2016). Control of complex weed flora through a single pre- or post-emergence herbicide application is a very challenging task, and it is likely that the use of the same herbicides over a prolonged period may contribute to herbicide resistance in weeds (Kim 1996). Applying several herbicides which have different active ingredients is to be encouraged for broad-spectrum weed control. The sequential application of pre-followed by post-emergence herbicides in rice has proved to be effective in controlling weed flora well without yield penalty (Ramesha *et al.* 2017, Zahan *et al.* 2018). At the same time, applying different herbicides in combination may reduce herbicide resistance (Mahajan and Chauhan 2015). Transplanting is facilitated by the application of herbicides, including pre-emergence herbicides options like pendimethalin, oxadiazon, oxadiargyl, pretilachlor, and post-emergence herbicides such as cyhalofop–butyl, bispyribac-sodium, penoxsulam, fenoxaprop, azimsulfuron, 2,4-D, metsulfuron-methyl, triafamone + ethoxysulfuron (Mishra *et al.* 2016, Arthanari 2023). However, the optimal time window for herbicide application, tailored to specific crop environments, remains crucial for effective weed suppression. Against this backdrop, a field experiment was conducted at the research farm of BCKV, Kalyani, to evaluate the response of rice and associated weed flora to new herbicides under transplanted conditions in a subtropical ecological setting. The objective of the experiment was to study the efficacy of pre- and post-emergence herbicides in managing weeds and improving productivity of rice under new alluvial zone. This study aims to contribute valuable insights into the sustainable management of weeds in transplanted rice, offering practical solutions for enhancing productivity in rice cultivation systems.

MATERIALS AND METHODS

A field study was carried out during *Kharif*, 2020 and 2021 at the research farm of BCKV, Kalyani (18.1243° N latitude, 84.5447° E longitude with an average altitude of 257 meters above mean sea level), India. The study site experienced an average annual rainfall of 1150 mm, with 85% received during the south-west monsoon. The region has a subtropical climate with hot summers and a mean minimum temperature of 22.7°C in January, while May is the hottest month with a mean maximum temperature of 43°C. The soil was of Arang Series with a clay loam texture containing 32.8% clay, 21.7% silt and 45.5% sand. The soil had a neutral pH of 6.8-7.2 and medium soil organic carbon content of 0.46%. The study was conducted with rice variety '*IET 4786*', (Shatabdi) at a spacing of 20 × 10 cm. The tested treatments were: oxadiargyl 80% WP (oxadiargyl) 0.1 kg/ha followed by (*fb*) post-emergence application (PoE) of 2,4-D 0.5 kg/ha 25 days after transplanting (DAT); pretilachlor 0.70 kg/ha PE; pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 10% SC (bispyribac-Na) 25 g/ha PoE at 25 DAT; pretilachlor 0.70 kg/ha PE *fb* cyhalofop-butyl 5.1% + penoxsulam 1.02% OD ready mix (RM) (cyhalofop-butyl + penoxsulam) 112.5 + 22.5 g/ha PoE at 25 DAT ; oxadiargyl 0.1 kg/ha *fb* passing of conoweeder; pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder; pretilachlor 0.70 kg/ha PE *fb* triafamone + ethoxysulfuron 44.0 + 22.5 g/ha PoE at 25 DAT; hand weeding twice at 20 and 40 DAT and weedy check. A randomized complete block design with four replications was used. The gross plot size was 5 m × 4 m. Herbicide application was done using a knapsack sprayer equipped with a flat fan nozzle using a spray volume of 500 L/ha. The crop was fertilized with 80: 40: 40 kg N, P and K/ha through urea (N) and muriate of potash (K), where the full dose of P and K fertilizers were applied at the time of transplanting. Nitrogen was applied in three splits at before transplanting, 30 and 60 DAT. Weed parameters (weed density and biomass) were recorded using quadrats, measuring 0.25 m^2 (0.5 m × 0.5 m dimension), placed at three random places in each of the plot at 60 DAT. Weeds of different groups were identified, counted and cut at collar portion of the plants and placed them separately in brown bags for sun drying for 3–5 days. After drying off the excess moisture, these paper bags were placed in an oven at 70±2°C for 72 hours until the weed samples attained a constant weight, which was considered the biomass of the respective weed species. The mean of both quadrats was converted into numbers/m^2 (weed density) and g/m^2(weed biomass), for analysis and interpretation. The weed control efficiency was calculated from total weed biomass. To homogenize the variance, a square root ($\sqrt{x+0.5}$) transformation was performed to the weed data (weed density and biomass). Yield attributes, including the number of panicles/m^2, the number of grains/ panicles, and the 1,000-grain weight (g) at harvest, were recorded from ten randomly chosen hills within each treatment. Data pertaining to grain yield and straw yield were recorded on per plot basis in kilograms. The entire plot was systematically harvested, dried, and weighed, with the recorded figures subsequently converted into metric tons per hectare (t/ha) to facilitate the comparative analyses. The influence of herbicides on yield was evaluated utilizing the following formulae.

$$\text{YOC}(\%) = \frac{\text{Yield from treated plot} - \text{yield from weedy check plot}}{\text{yield from weedy check plot}} \text{ x } 100$$

$$\text{RYL}(\%) = \frac{\text{Yield from weed free plot} - \text{yield from treatment plot}}{\text{yield from weed free plot}} \text{ x } 100$$

Where,

YOC = Yield over check

RYL = Relative yield loss

Statistical analysis of all field data was conducted using SAS statistical software (version 9.3). The Tukey's Honest Significant Difference test was selected, and analysis of variance (ANOVA) was performed to determine the level of significance (p=0.05) between treatment means. As the effect of year was not that significant in most of the cases, results were presented as pooled data of two years.

RESULTS AND DISCUSSION

Weed flora

Ten distinct weed species, categorized into grasses, broad-leaved weeds (BLW), and sedges, were identified. *Cynodon dactylon* weed exhibited varying occurrences across different herbicide treatments, with noteworthy contributions to the total weed population (**Table 1**). *Cynodon dactylon* was recorded in plots treated with oxadiargyl 0.1 kg/ha PE *fb* passing of conoweeder, pretilachlor 0.70 kg/ha PE, and pretilachlor 0.70 kg/ha PE *fb* cyhalofop-butyl + penoxsulam (RM) 112.5 + 22.5 g/ha PoE, with respective contributions of 27.30%, 23.9% and 19.93% of the total weed density. The presence of *Panicum repens* was significantly affected by herbicide applications. The combination of pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder resulted in the lower density of *Panicum repens*. The distribution of *P. repens* in the order of decreasing density in response to post-emergence herbicide application was: pretilachlor PE *fb* triafamone + ethoxysulfuron PoE > pretilachlor PE *fb* cyhalofop-butyl + penoxsulam PE > pretilachlor PE *fb* bispyribac-Na PoE > hand weeding twice at 20 and 40 DAT, with percentage shares of 31.25%, 28.69%, 36.19%, and 30.33%, respectively. *Ludwigia parviflora* was observed only with oxadiargyl 0.1 kg/ha PE *fb* 2,4-D 0.5 kg/ha PoE (1.97 no./m^2) and weedy check (6.74 no./m^2). *Eclipta alba* dominated the overall weed flora, with the highest density in non-treated weedy check plots, followed by oxadiargyl 0.1 kg/ha PE *fb* 2,4-D 0.5 kg/ha PoE, pretilachlor 0.70 kg/ha, and hand weeding twice at 20 and 40 DAT. The treatments with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder and pretilachlor 0.70 kg/ha PE *fb* triafamone + ethoxysulfuron 44.0 + 22.5 g/ha PoE recorded the lowest density of *Eclipta alba.* Rishi *et al.* (2016) observed that the sequential application of pendimethalin PE *fb* bispyribac-sodium PoE significantly reduced the *Eclipta alba*, *Echinochloa colona* density as compared to single application of pendimethalin PE, butachlor PE and oxydiargyl PE, ethoxysulfuron PoE and bispyribac-sodium PoE and weedy check at 30 and 90 DAT stage of rice respectively. Similar results were reported by Singh *et al.* (2016).

The density of *Cyprus iria* was highest in weedy check, followed by pretilachlor 0.70 kg/ha PE, hand weeding twice at 20 and 40 DAT, and pretilachlor 0.70 kg/ha PE *fb* cyhalofop-butyl + penoxsulam 112.5 + 22.5 g/ha PoE. Maximum biomass of *Echinochloa colona* was in the weedy check, followed by pretilachlor 0.70 kg/ha PE. However, pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder resulted in best control of *Echinochloa colona*. *Malva neglecta* density was least with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder, while highest with oxadiargyl 0.1 kg/ha PE *fb* 2,4-D 0.5 kg/ha PoE. *Fimbristylis miliacea* was observed only with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder and its highest density was found in weedy check, among all other treatments. Reductions in the density of grasses like *Echinochloa* spp. was previously observed with pretilachlor widely across South Asia (Hossain *et al.* 2020, Chatterjee *et al.* 2021, Rao *et al.* 2007, Singh *et al.* 2015). Most of the pre-emergence herbicides lack efficacy against sedge weeds, particularly on those which multiply through rhizomes and stolon rather than by cell division; thus, the pre-emergence herbicides tested here were less effective against sedges (Rao *et al.* 2007, Singh *et al.* 2015, Hossain *et al.* 2020, Chatterjee *et al.* 2021)

Pre-emergence herbicides alone were not effective at preventing the establishment of weeds at later dates due to their relatively short-lived persistence under hot and moist conditions (Saha et al. 2021). Post-emergence herbicides, the bispyribac alone or bispyribac + pyrazosulfuron not only controlled both grassy and broad-leaved weed well but also effectively controlled sedges, particularly *Cyrus iria* which is a major sedge weed in the region (Jat *et al.* 2021, Saha *et al.* 2021). Similarly, Mitra *et al*. (2022) also reported the maximum biomass reduction of all weeds at both 35 and 55 DAT with the sequential application of pendimethalin PE fb bispyribac + pyrazosulfuron PoE.

Weed control

In the experimental fields, a diverse weed flora was observed across various treatments, and the total weed population dynamics were influenced by different weed management strategies (**Table 2**). In comparison to the weedy check, the treatments tested exhibited lower densities of grasses, BLW, and sedges. Notably, treatments with pretilachlor were predominantly infested by grassy weeds, while BLW weeds dominated the weed flora in other treatments. Plots treated with pendimethalin followed by 2,4-D were primarily infested with sedges. Strikingly, the application of pretilachlor followed by bispyribac sodium resulted in the lowest density of grasses and sedges, while a few grasses at 60 DAT were observed with triafamone+ ethoxysulfuron, but complete control was achieved as the days from sowing progressed. Notably, the herbicide treatments involving triafamone+ ethoxysulfuron PoE and pretilachlor followed by bispyribac-sodium demonstrated superior efficacy in controlling a majority of weed species. Triafamone+ ethoxysulfuron herbicide is acetolactate synthase (ALS) inhibitors working on the principle of halting the flow of assimilate supply to sink thereby inhibiting weed growth (Aranthari *et al.* 2023). Furthermore, the advantages associated with triamafone + ethoxysulfuron can be accounted for its greater availability encompassing both foliar and root pathways. *Ammania* spp. and *Eclipta* spp., although in limited numbers, were the only weed species observed with triafamone+ethoxysulfuron. This observation can be potentially attributed to its greater phenotypic plasticity and persistent seed bank encouraging multiple-year germination (Caton *et al.* 1997). Pretilachlor *fb* bispyribac-sodium demonstrated efficacy due to the mode of action of pretilachlor involves inhibiting the biosynthesis of fatty acids in the target weeds. Pretilachlor works by preventing the target plants from synthesizing very long chain fatty acids. Grassy weeds in rice crops are the main target of pretilachlor, a herbicide belonging to the chloroacetamide group. Pretilachlor is absorbed by the roots or absorbed via the leaves of plants when it is applied to their soil or foliage, and it is subsequently transferred throughout the plant. Once within the plant, pretilachlor prevents the Acetyl-CoA carboxylase enzyme, which is responsible for fatty acid production. Pretilachlor interferes with the synthesis of vital fatty acids required for the target plants' growth and development by blocking ACCase. Plants cannot build

Table 1. Effect of herbicide on the density of different weeds in transplanted rice at 60 DAT (two years pooled data)

Treatment	Weed density (no./ m^2)									
	Grasses			Broad-leaved weeds					Sedges	
	Cynodon dactylon	*Echinochloa colona*	*Panicum repens*	*Ludwigia parviflora*	*Alternanthera philoxeroides*	*Malva neglecta*	*Eclipta alba*	Other BLW	*Cyrus iria*	*Fimbristylis miliacea*
Oxadiargyl 0.1 kg/ha PE *fb* 2,4-D 0.5 kg/ha PoE	1.99 (3.48)	2.71 (6.82)	2.46 (5.55)	1.57 (1.97)	1.78 (2.66)	2.32 (4.86)	2.50 (5.77)	2.27 (4.65)	1.83 (2.84)	1.57 (1.96)
Pretilachlor 0.70 kg/ha PE	2.14 (4.07)	3.03 (8.70)	3.85 (7.65)	1.53 (1.85)	1.81 (2.78)	2.25 (4.55)	2.48 (5.63)	2.34 (4.99)	1.96 (3.36)	1.65 (2.23)
Pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE	1.74 (2.54)	2.22 (4.41)	2.11 (3.96)	1.14 (0.79)	1.23 (1.00)	1.77 (2.64)	2.27 (4.65)	2.09 (3.88)	1.57 (1.95)	1.32 (1.23)
Pretilachlor 0.70 kg/ha PE *fb* cyhalofop-butyl 112.5 + 22.5 g/ha (RM) PoE	2.01 (3.53)	2.49 (5.68)	2.05 (3.71)	1.44 (1.56)	1.48 (1.7)	2.16 (4.17)	2.41 (5.31)	2.24 (4.5)	1.77 (2.63)	1.49 (1.72)
Oxadiargyl 0.1 kg/ha as PE *fb* passing of conoweeder	2.16 (4.18)	2.75 (7.04)	2.59 (6.20)	1.54 (1.86)	1.91 (3.15)	2.18 (4.23)	2.46 (5.55)	2.34 (4.99)	1.87 (2.99)	1.61 (2.10)
Pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder	1.58 (1.98)	2.04 (3.67)	1.89 (3.06)	1.14 (0.81)	1.14 (0.80)	1.40 (1.45)	2.07 (3.80)	1.73 (2.48)	1.51 (1.78)	1.26 (1.09)
Pretilachlor 0.70 kg/ha PE *fb* triafamone+ ethoxysulfuron (44.0+22.5 g/ha) PoE	1.81 (2.78)	2.38 (5.15)	2.03 (3.61)	1.32 (1.23)	1.34 (1.30)	2.03 (3.61)	2.24 (4.51)	2.16 (4.14)	1.63 (2.16)	1.36 (1.34)
Hand weeding twice at 20 and 40 DAS	2.02 (3.57)	2.66 (6.55)	2.20 (4.32)	1.56 (1.92)	1.72 (2.47)	2.22 (4.45)	2.48 (5.63)	2.22 (4.42)	1.78 (2.67)	1.54 (1.86)
Weedy check (control)	3.19 (9.67)	4.89 (23.45)	4.58 (20.47)	2.69 (6.74)	2.97 (8.32)	3.21 (9.82)	3.96 (15.18)	4.25 (17.54)	2.69 (6.76)	2.23 (4.45)
LSD (p=0.05)	0.30	0.77	0.69	0.14	0.21	0.31	0.5	0.41	0.28	0.19

PE = pre-emergence application; PoE = post emergence application; DAT = days ater transplanting vital cell membranes and other lipid-containing structures if they do not have a sufficient supply of fatty acids, which inhibits growth and ultimately results in death (Shilpakar *et al.* 2020). After that bispyribac-sodium consists in the inhibition of the branched amino acid biosynthesis. This substance exhibits a favourable eco-toxicological profile, effectively disrupting the growth of various weed species across multiple cycles. Our findings regarding pretilachlor *fb* bispyribac-sodium align with Chaudhury and Dixit (2024), indicating its greater effectiveness against *Echinochloa crusgalli* when applied at 25 DAT. However, triafamone+ ethoxysulfuron and pretilachlor treatments exhibited good result in the control of grasses and sedges as observed earlier by Yadav *et al.* (2019). Additionally, the sequential application of pretilachlor *fb* 2,4-D demonstrated effective control of BLW. Jehangir *et al.* (2022) also highlighted the effectiveness of penoxsulam against both grasses and sedges up to 60 DAT.

Among the herbicide-based treatments, pretilachlor 0.70 kg/ha *fb* passing of conoweeder reduced grasses by 90.34%, broad-leaved weeds by 92.87%, sedges by 81.54% and total weed by 88.68%. Next effective treatments were pretilachlor PE *fb* bispyribac-sodium PoE (89.34, 87.23, 80.61 and 86.28%, respectively) and pretilachlor 0.70 kg/ha PE *fb* triafamone + ethoxysulfuron 44.0+22.5/ha PoE over the weedy check. Suppression of weeds reduced the total weed biomass, resulting in a higher WCE in the sequential application of PE *fb* PoE herbicides. The sole application of pretilachlor was also weak as it controlled only 21-34%, 15-19% and 7-13% of grasses, BLW and sedges, respectively. Thus, using only pre- or post-emergence herbicides is not efficient enough to provide broad-spectrum weed control. Sequential use of pre-emergence herbicides such as pretilachlor followed by post-emergence herbicide (bispyribac-sodium) broadly controls mixtures of weed flora in transplanted rice. This is because broad-leaved weeds, sedges and some grasses were effectively controlled by bispyribac-sodium, whereas pretilachlor takes care of grasses and some broad-leaved weeds. Subsequent applications of bispyribac-sodium control the large group of weeds left after PE herbicide or late emerged weeds. Applications of PE herbicides significantly suppress initial weed establishment, and subsequently, bispyribac-sodium 25 g/ha takes care of the weeds at a later crop stage. Similarly, application of PE and PoE herbicides in sequence or compatible tank mix or premix herbicides with different mode of action is superior to weedy check in controlling weeds (**Tables 1** and **2**).

Weed Indices

The weed biomass was significantly influenced by weed control treatments (**Table 2**). The highest weed biomass was recorded in weedy plots, whereas hand weeding twice at 20 and 40 DAT recorded the minimum. Among the herbicides, pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder followed by pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE and triafamone+ ethoxysulfuron PoE treatments recorded significantly lower weed biomass at 60 DAT. The performance of pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE was also better than the herbicides applied alone. Pretilachlor and oxadiargyl alone were less effective than the other herbicides, but all the herbicides were better than weedy check during both the years.

Table 2. Effect of herbicides on the weed density and biomass and rice growth parameters in transplanted rice at 60 DAT (two years pooled data)

Treatment	Weed density (no./ m^2)	Weed biomass (g/ m^2)	WCE (%)	WI (%)	Rice plant Height (cm)	Rice plant dry matter accumulation (g/m^2)
Oxadiargyl 0.1 kg/ha PE *fb* 2,4-D 0.5 kg/ha PoE	4.04(15.86)	3.68(13.07)	76.3	22.42	100.57	621.50
Pretilachlor 0.70 kg/ha as PE	4.57(20.42)	4.15(16.71)	68.81	27.66	98.655	595.90
Pretilachlor 0.70 kg/ha as PE *fb* bispyribac-Na 25 g/ha as PoE	3.38(10.94)	2.82(7.47)	86.74	4.45	108.48	676.05
Pretilachlor 0.70 kg/ha as PE *fb* cyhalofop-butyl 112.5 + 22.5 g/ha (RM) as PoE	3.66(12.93)	3.36(10.80)	80.31	15.58	103.20	706.68
Oxadiargyl 0.1 kg/ha as PE *fb* passing of conoweeder	4.23(17.42)	3.93(14.94)	72.67	25.44	99.05	618.56
Pretilachlor 0.70 kg/ha as PE *fb* passing of conoweeder	3.04(8.72)	2.64(6.47)	88.68	0.00	112.11	683.92
Pretilachlor 0.70 kg/ha as PE *fb* triafamone + ethoxysulfuron 44.0 + 22.5 g/ha PoE	3.47(11.55)	3.16(9.50)	82.86	10.33	104.98	667.34
Hand weeding twice at 20 and 40 DAS	3.87(14.44)	3.55(12.12)	78.13	18.76	102.19	686.87
Weedy check (control)	7.36(53.6)	7.48(55.45)	0	54.21	86.91	525.34
LSD (p=0.05)	1.88	2.03	-	-	6.47	47.89

PE = pre-emergence application; PoE = post emergence application; DAT = days ater transplanting

The weed control efficiency was largely depended on weed biomass but influenced largely by weed control treatments (**Table 2**). The highest weed control efficiency was obtained with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder (88.68%) and it was closely followed by pretilachlor 0.70 kg/ha PE *fb* triafamone + ethoxysulfuron 44.0+22.5 g/ha PoE (82.86%) and pretilachlor 0.70 kg/ha *fb* bispyribac-Na 25 g/ha (86.74%). These treatments were comparable to each other. This is contrary to the results of Meera and Menon (2019) who noticed the highest weed control efficiency with triafamone + ethoxysulfuron. Pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder recorded the lowest WCE at 60 DAT (68.81%). Moreover, the observed increase in WCE at later stages of the crop may be attributed to the canopy closure, resulting in a smothering effect on weed growth. The better weed control was recorded due to timely sowing of crop and herbicide application, which are prerequisite to obtain the better efficacy. Herbicide combinations widen the spectrum of weed control (Singh and Singh 2012). Pre-mix of triafamone + ethoxysulfuron increased broad spectrum weed control (grasses, BLW and sedges). Notably, WCE tended to increase as the crop approached maturity. Among herbicides, pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder recorded the least WI value of (4.27) and a higher rice plant height and rice plant dry matter accumulation (**Table 2**).

The observed weed density and biomass indicated that pretilachlor effectively controlled grasses and to some extent BLW, but its efficacy was poor on sedges. Bispyribac-Na 25 g/ha PoE resulted in lesser BLW and sedges than the grasses. The pre-mix of triafamone + ethoxysulfuron had additive effect on controlling wide range of weeds and effective against grasses, broad-leaved weeds and sedges confirming earlier findings (Mahajan and Chauhan 2013). The broad-spectrum nature of triafamone, coupled with its diverse mechanisms of availability through foliage and soil residue activity might have contributed to its effective weed management (Rosinger *et al.* 2012). Arthanari (2023) also observed the higher WCE with triafamone + ethoxysulfuron PoE. The lower values of WI value associated with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder, indicate its broad-spectrum weed control efficacy confirming observations of Sen *et al.* (2020) and Meena *et al.* (2019).

Rice yield and yield attributes

Weed control treatments exerted a significant impact on rice yield attributes and grain yield. In comparison to the weedy check, all other treatments demonstrated higher rice yield attributes and grain yield. Specifically, pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder produced the highest panicle length (2.92 cm), grains/panicle (138.14), and 1,000-grain weight (22.08 g), closely followed by pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE (**Table 3**).

Weed-free yielded the highest rice grain yield, but was not significantly different from grain yield with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder. These treatments were statistically at par with rice grain yield recorded with pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE 25 DAT and pretilachlor 0.70 kg/ha PE *fb* triafamone + ethoxysulfuron (44.0 + 22.5 g/ha) PoE. This notable increase in grain yield can be attributed to the effective mitigation of weed competition by pre-emergence herbicides during the early stages. This early intervention curtailed weed growth during the initial growth phase of the crop. Furthermore, the subsequent application of post-emergent (PoE) measures further controlled subsequent flushes of weed emergence, thereby ensuring comprehensive weed management throughout the entire crop cycle. This combined PE and PoE approach collectively contributed to the improved crop growth conditions, ultimately leading to enhanced grain yield. The rice grain yield increase ranged from 61.20% to 123.64% with pretilachlor

Table 3. Effect of herbicides on rice growth parameters and rice yield in transplanted rice (two years pooled data)

Treatment	Rice grain yield (t/ha)	YOC (%)	RYL (%)	Panicle length (cm)	No. of grains/ panicle	1000 seed weight (g)
Oxadiargyl 0.1 kg/ha *fb* 2,4-D 0.5 kg/ha PoE	4.84	72.24	23.08	24.47	126.64	19.39
Pretilachlor 0.70 kg/ha PE	4.53	61.20	28.14	22.32	116.43	18.14
Pretilachlor 0.70 kg/ha as PE *fb* bispyribac-Na 25 g/ha as PoE	6.02	114.23	4.29	28.09	135.42	21.31
Pretilachlor 0.70 kg/ha PE *fb* cyhalofop-butyl 112.5 + 22.5 g/ha (RM) PoE	5.32	89.32	15.57	25.27	133.02	19.90
Oxadiargyl 0.1 kg/ha PE *fb* passing of conoweeder	4.61	64.05	26.91	23.81	122.28	19.10
Pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder	6.29	123.84	0	28.92	138.14	22.08
Pretilachlor 0.70 kg/ha PE *fb* triafamone+ ethoxysulfuron (44.0+22.5) PoE	5.62	100	10.72	26.49	134.52	21.02
Hand weeding twice at 20 and 40 DAS	5.11	81.85	18.71	25.02	130.08	19.95
Weedy check (control)	2.81	0	55.47	21.20	103.26	16.49
LSD (p=0.05)	0.16	-	-	0.73	9.71	0.79

PE = pre-emergence; PoE = post-emergence; DAT = days ater transplanting; YOC = yield over check; RYL = relative yield loss

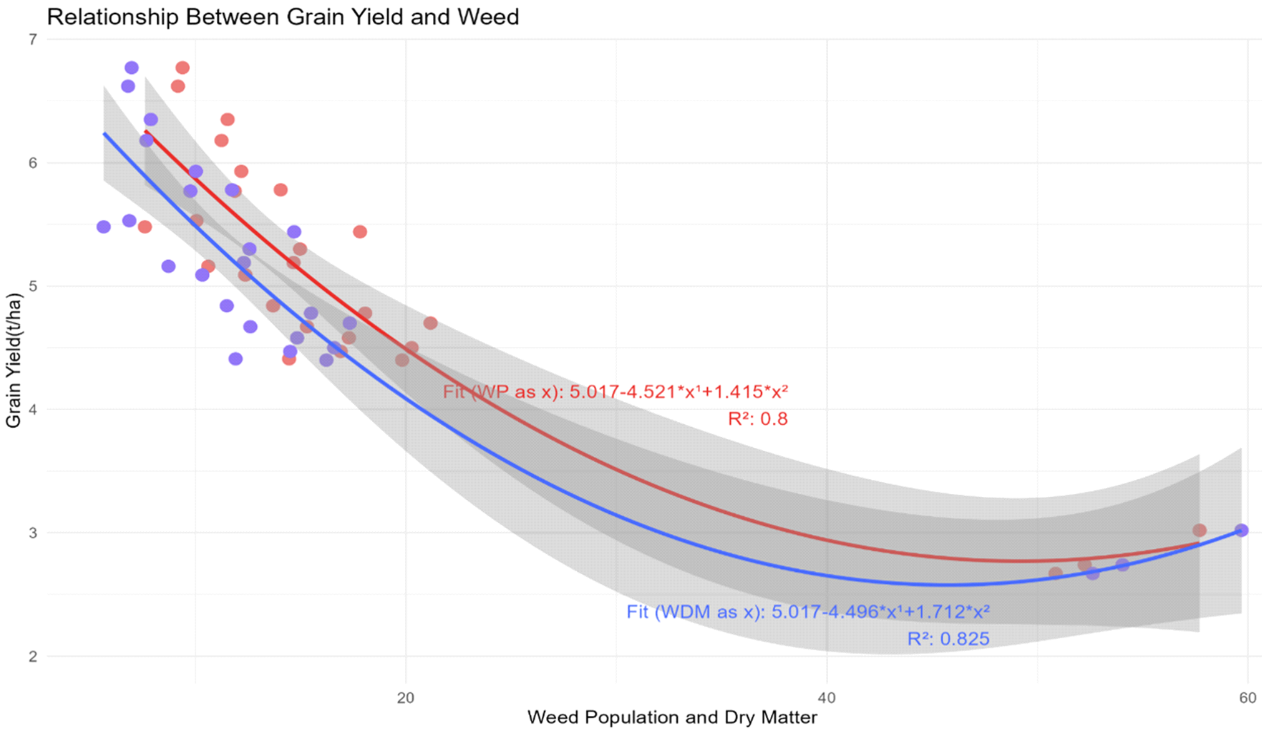

Figure 1. Relationship between grain yield and weed parameters

0.70 kg/ha PE *fb* passing of conoweeder and pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE. Similar increase was observed earlier by Kaur and Singh (2015), Singh *et al.* (2016), Saha *et al.* (2021) and Mitra *et al.* (2022). The recorded minimum grain yield was observed in the weedy control due to the unweeded weeds competition for essential resources (Choudhary *et al.* 2021).

The rice yield reduction due to weed interference ranged from 1% to 58.39% (**Table 3**) across the treatments tested with maximum yield loss of 58.39% in weedy check. Pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder recorded lower yield loss of 1% followed by pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha PoE with 4.29% yield loss due to uncontrolled weeds. Grain yield exhibits a negative correlation with weed density and biomass. To capture this relationship, a second order polynomial model was employed to describe the variation of grain yield concerning changes in weed density and dry weight. The model yielded an R-squared value of 0.8 and 0.825 (**Figure 1**).

Conclusions

It may be concluded that in transplanted rice grown at the new alluvial zone of West Bengal, the effective weed management and increased rice yield can be obtained with pretilachlor 0.70 kg/ha PE *fb* bispyribac-Na 25 g/ha as PoE or with pretilachlor 0.70 kg/ha PE *fb* passing of conoweeder.

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RESEARCH ARTICLE

Effect of herbicides on weeds and direct-seeded rice growth and yield

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ABSTRACT

A study was carried out during 2022 and 2023 in Raipur, Chhattisgarh with an objective to study the effect of sequential pre-emergence application (PE) followed by (*fb*) post-emergence application (PoE) of herbicides on weed management and grain yield of direct-seeded rice (DSR). Weed flora associated with DSR were: *Alternanthera sessilis, Cyanotis axillaris, Echinochloa colona*, *Cyperus iria.* Pendimethalin 1000 g/ha PE *fb* tank mixed bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl ready mix (RM) 4 g/ha PoE at 25 to 30 days after seeding (DAS) reduced weed density with higher rice plant height, leaf area and maximum rice grain yield, which was comparable with pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE 25-30 DAS and hand weeding twice at 30 and 60 DAS. It was concluded that pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE at 25-30 DAS effectively managed weeds in direct-seeded rice which resulted in maximum rice growth and yield as well as maximum net return and B:C ratio.

Keywords: Direct-seeded rice, Metsulfuron-methyl + chlorimuron-ethyl, Pendimethalin, Penoxsulam + cyhalofop-butyl, Weed management

INTRODUCTION

Rice (*Oryza sativa* L.) is a primary food crop grown widely over 162 million hectares in more than hundred countries of the world (Anonymous 2022) with an annual global production of about 680.7 million tons (Anonymous 2022a). It is the staple food for more than half of the world's population. In India, rice is the major food grain crop and an important part of the national economy, cultivated in an area of 47.83 million hectares, with a production and productivity of 135.7 MT and 2.83 t/ha, respectively (Anon 2023) and accounted for over Rs. 1.8 trillion in the Indian economy (Anonymous 2020b). Chhattisgarh accounts for 3.82 Mha area with a production of 7.82 MT and productivity of 2.04 t/ha in the state (Anonymous 2023).

The direct-seeding of rice (DSR) results in the increased efficiency of time, energy, water, and labor costs (Rao *et al*. 2007). Despite of several advantages, heavy weed infestation is one of the major constraints in direct-seeded rice since weeds cause severe rice yield losses. Herbicide usage for weed management is becoming the popular method of weed control in rice, because of lower costs involved (Rao *et al*. 2017). But, weed shift from grasses to non-grasses and annual sedges is being observed in rice field due to continuous use of high dose of herbicides like pendimethalin, pyrazosulfuron-ethyl *etc*. (Singh *et al*. 2017). These herbicides provide effective control of annual grasses when applied as pre-emergence, rendering an effective control during the first 20 to 25 days. Later emerging weeds at later stages of rice growth becomes uncontrollable causing considerable loss of rice yield, besides adding weed seeds to the seed bank of the soil. Hence, to achieve weed control at the later stages, pre-emergence application of herbicides alone is not sufficient to adequately manage weeds. Thus, sequential application of both pre- and post-emergence herbicides is essential to achieve broad spectrum weed control during critical period so as to realize the yield potential of rice. Pre- and post-emergence herbicides offer selective, timely, effective, and cost-efficient weed control rather than manual weeding (Jayadeva *et al*. 2011). Hence, a study was carried out with an objective to study the effect of sequential pre-emergence application (PE) followed by (*fb*) post-emergence application (PoE) of herbicides on weed management, crop growth, and rice yield in direct-seeded rice.

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MATERIALS AND METHODS

This experiment was conducted during the *Kharif* 2022 and 2023 at Research cum Instructional Farm, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh. Raipur is situated in south eastern part of Chhattisgarh at 21o23'N latitude and 81o71'E longitude at the height of 290.20 m above the mean sea level (MSL). The soil of the experimental field was clayey in texture and neutral (pH 7.18) in reaction with medium fertility having 0.39% soil organic carbon, low nitrogen (255 kg/ha), medium phosphorous (17.40 kg/ha) and high potassium (370 kg/ha), respectively.

The experiment was laid out in randomized block design (RBD) with three replications and seven treatments, *viz*. pendimethalin + pyrazosulfuron-ethyl ready mix (RM) 785 g/ha PE followed by (*fb*) one hand weeding (HW) at 30 days after seeding (DAS), penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE at 25-30 DAS, penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE at 25-30 DAS, pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE at 25-30 DAS, pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE 25-30 DAS, hand weeding (HW) twice at 30 and 60 DAS, partially weedy check with HW once at 60 DAS. The rice variety "Indira Rajeshwari (IGKV R 1)" was sown on 1st July 2022 and 3rd July 2022 and harvested on 3rd November 2022 and 15 November 2023. The crop received 783 and 855 mm rainfall during the crop period in 2022 and 2023, respectively. The rainfall received was more in 2023 and hence the field remained filled with water for a long time with lesser weed infestation and higher rice tillering, plant height and higher yield than 2022 *Kharif* season.

Herbicides were applied as per the treatments mentioned in experimental details. Pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha, penoxsulam + pendimethalin (RM) g/ha, pendimethalin 1.0 kg/ha spraying was done 2 days after sowing (DAS). The bispyribac-sodium 25 g/ha, fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha, metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix, penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE were applied as sequential post-emergence herbicides at 25-30 DAS, as per the treatment details. For herbicides application, hand operated knapsack sprayer was used which was fitted with flat fan deflector nozzle. For the herbicide application water (500 liters/ha) was used as carrier.

Rice plant height and leaf area data was collected from the experimental plots at 20, 40, 60, 90 DAS and at harvest. The rice grain yield was collected and economic analysis was done using standard procedures. Total and species wise weed density associated with DSR in the experimental plots were recorded at 40 DAS. Weed count was done from three spots using quadrat of 0.5 m x 0.5 m (0.25 m^2) randomly placed in each plot. The number of weeds were counted and the density was expressed as number/m^2. Weed density data was subjected to square root transformation *i.e.*, $\sqrt{x+0.5}$, for statistical analysis.

RESULTS AND DISCUSSION

Weed flora

The weed flora of the experimental field consisted of *Alternanthera sessilis, Cyanotis axillaris, Echinochloa colona, Cyperus iria*. The *Alternanthera sessilis, Cyanotis axillaris* dominated the weed flora during entire vegetative growth stage and were present during later stages of the crop too. The occurrence of other weeds like *Celosia argentea, Phyllanthus niruri*, etc. was uneven with lesser density.

Effect on rice

Rice plant height gradually increased with age of the crop and reached to its maximum at harvest. At 20 DAS, rice plant height was not-significantly amongst tested treatments. At 40, 60 and 90 DAS, significantly taller rice plant, higher leaf area was registered with pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE as compared to other treatments, but it was at par with pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop butyl (RM) 135 g/ha PoE, and HW twice at 30 and 60 DAS (**Table 1**). The minimum plant height was recorded in partially weedy check (HW once at 60 DAS) during both years of study. Similar trend was also observed at harvest.

Weeds compete with rice plants for light. Leaf area determines light interception and is an important parameter in determining plant productivity (Koester *et al.* 2014). The higher rice leaf area in the effective treatments minimized the light availability to weeds and hence caused lower weed biomass. When weed density is low, rice plants receive more sunlight, which is essential for photosynthesis. Adequate light helps rice plants grow taller as they can photosynthesize more efficiently and allocate resources towards vertical growth. Weeds can deplete soil nutrients and affect their availability to rice plants. With fewer weeds competing for nutrients, rice plants can access a higher amount of essential nutrients like nitrogen, phosphorus, and potassium. This improved nutrient availability supports better overall growth and contributes to increased plant height, same condition for water. Similar findings were reported by Sanodiya and Singh (2018) and Ramachandiran and Balasubramanian (2012).

The highest rice grain yield **(**6.56 and 6.69 t/ha**)** was recorded with pendimethalin 1.0 kg/ha as PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE (**Table 2**). It was found at par with pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE, HW twice at 30 and 60 DAS and penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE. The partially weedy check (HW once at 60 DAS) recorded reduction in grain yield of 61% and 56 % in comparison to best treatment during 2022 and 2023, respectively.

Pendimethalin pre-emergent spray inhibited root and shoot growth and controlled the weeds growth by preventing weeds from emerging, particularly during the crucial development phase of the crop. Pendimethalin controlled *Echinochloa colonum, Cyanotis axillaries* and *Cyperus* spp. and penoxsulam moving throughout plant tissue prevented it from producing acetolactate synthase, a necessary enzyme for growth. Cyhalofop-butyl is an inhibitor of acetyl coenzyme -A carboxylase, targeting *Echinochloa colona*,

Table 1. Rice plant height at different periods of crop growth as influenced by different weed management treatments

Treatment	Rice plant height (cm)									
	20 DAS		40 DAS		60 DAS		90 DAS		At harvest	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha PE *fb* HW once at 30 DAS	31.3	33.4	58.5	62.4	82.5	84.5	97.4	99.5	104.5	105.5
Penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE	30.5	31.6	57.5	54.5	80.6	81.2	95.5	92.5	103.7	104.5
Penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE	32.4	34.5	60.2	63.3	85.5	87.6	101.5	104.9	105.7	106.6
Pendimethalin 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE	33.6	36.4	67.6	71.5	90.4	93.4	104.7	106.7	109.4	111.4
Pendimethalin 1000 g/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE	33.4	35.3	65.6	69.2	88.5	90.4	103.4	105.1	107.4	109.3
Hand weeding (HW) twice at 30 and 60 DAS	33.1	35.1	62.4	67.6	87.8	89.6	103.5	106.4	107.08	108.1
Partially weedy check (HW once at 60 DAS)	29.8	30.1	54.6	50.5	75.2	78.0	85.4	89.5	101.69	102.6
LSD (p=0.05)	3.61	3.98	7.44	4.89	5.57	4.21	5.58	3.61	2.61	4.14

* PE =pre-emergence application; PoE = post-emergence application; DAS = days after seeding, RM = ready mix

Table 2. Leaf area at different periods of crop growth and rice grain yield as influenced by different weed management treatments

Treatment	Leaf area (cm^2/m^2)						Grain yield (t/ha)	
	20 DAS		40 DAS		60 DAS			
	2022	2023	2022	2023	2022	2023	2022	2023
Pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha PE *fb* HW once at 30 DAS	266.9	271	433.3	436	894.4	899	5.82	6.08
Penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE	265.4	267	430.5	433	885.4	890	5.62	5.89
Penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE	264.1	268	438.3	441	899.3	905	6.02	6.30
Pendimethalin 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE	266.3	269	450.4	456	912.2	917	6.56	6.69
Pendimethalin 1.0 Kg/ha PE *fb* penoxsulam + cyhalofop- butyl (RM) 135 g/ha PoE	263.8	265	447.3	453	908.5	912	6.25	6.51
HW twice at 30 and 60 DAS	262.2	264	443.5	449	905.5	909	6.12	6.45
Partially weedy check (HW once at 60 DAS)	263.2	267	290.3	295	510.0	465	2.50	2.92
LSD (p=0.05)	3.98	4.30	6.67	7.07	9.81	8.05	0.68	0.49

*HW = Hand weeding; PE =Pre-emergence application; PoE = post-emergence application; DAS = days after seeding, RM = ready mix

Echinochloa crus-galli, Alternanthera sessilis, Cyperus difformis, Cyperus iria, at critical stage of crop weed competition resulting in less weed biomass with better suppression of weeds, which allowed the crop to grow with its potential as compared to other treatments

Effect on weeds

Pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE at 25-30 DAS has significantly reduced the density of *Alternanthera sessilis* and it was at par with pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE and penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE during both years (**Table 3**). Partially weeded check recorded significantly highest weed density of *Alternanthera sessilis* during both years.

At 40 DAS, HW twice at 30 and 60 DAS recorded significantly lowest *Cyanotis axillaris* density and it was at par with pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE, pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha PE (*fb*) HW once and penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE during both the years. *Echinochloa colona* was absent at 40 DAS in these treatments. *Cyperus iria* was absent at 40 DAS with application of penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE, pendimethalin 1.0 kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE and penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE (**Table 3**).

HW twice at 30 and 60 DAS recorded significantly lower weed density and at 40 DAS it was at par with pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + metsulfuron-methyl + chlorimuron-ethyl (RM) 4 g/ha tank mix PoE, during both years.

Table 3. The density (no./m^2) of dominant weed species at 40 DAS as influenced by different weed management treatments

Treatment	*Alternanthera sessilis*		*Cyanotis axillaris*		*Echinochloa colona*		*Cyperus iria*		Others		Total	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha PE *fb* HW once at 30 DAS	2.68 (6.66)	2.39 (5.20)	1.77 (2.62)	1.61 (2.11)	1.18 (0.89)	1.11 (0.73)	1.40 (1.45)	1.34 (1.30)	1.92 (3.19)	2.15 (4.13)	3.91 (14.82)	3.74 (13.46)
Penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha	1.97 (3.38)	1.92 (3.18)	3.45 (11.42)	3.32 (10.50)	1.54 (1.88)	1.48 (1.70)	0.71 (0.00)	0.71 (0.00)	2.30 (4.81)	2.16 (4.18)	4.69 (21.49)	4.48 (19.57)
Penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE	3.28 (10.28)	3.06 (8.86)	1.97 (3.36)	1.91 (3.15)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	2.46 (5.55)	2.62 (6.37)	4.44 (19.19)	4.34 (18.37)
Pendimethalin 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE	1.54 (1.89)	1.48 (1.70)	1.74 (2.53)	1.61 (2.10)	1.02 (0.53)	1.06 (0.62)	1.07 (0.64)	1.00 (0.51)	2.06 (3.73)	1.75 (2.55)	3.13 (9.32)	2.83 (7.49)
Pendimethalin 1000 g/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE	2.05 (3.72)	2.00 (3.48)	2.21 (4.39)	2.00 (3.52)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	2.86 (7.69)	2.61 (6.30)	4.04 (15.80)	3.72 (13.31)
Hand weeding (HW) twice at 30 and 60 DAS	2.47 (5.59)	2.37 (5.10)	1.72 (2.44)	1.65 (2.23)	1.06 (0.63)	1.03 (0.55)	1.41 (1.50)	1.30 (1.20)	1.63 (2.15)	1.55 (1.91)	3.58 (12.31)	3.39 (10.99)
Partially weedy check (HW once at 60 DAS)	6.07 (36.38)	5.84 (33.56)	4.78 (22.32)	4.58 (20.45)	4.37 (18.62)	4.57 (20.42)	3.70 (13.16)	3.32 (10.55)	3.85 (14.33)	3.36 (10.76)	10.26 (104.81)	9.81 (95.75)
LSD (p=0.05)	0.78	0.33	0.62	0.55	0.35	0.16	0.41	0.21	0.65	0.44	0.94	0.57

* PE =pre-emergence application; PoE = post-emergence application; DAS = days after seeding, RM = ready mix

Table 4. Economics of direct-seeded rice as influenced by different weed management treatments

Treatment	Cost of Cultivation (₹/ha)		Gross return (₹/ha)		Net return (₹/ha)		B:C ratio	
	2022	2023	2022	2023	2022	2023	2022	2023
Pendimethalin + pyrazosulfuron-ethyl (RM) 785 g/ha PE *fb* HW once at 30 DAS	32716	33579	118796	132726	86080	99147	2.63	2.95
Penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE	33079	33123	114580	128579	81501	95456	2.46	2.88
Penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE	34200	34244	122808	137529	88608	103285	2.59	3.02
Pendimethalin 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE	33355	33799	133824	146043	100469	112244	3.01	3.32
Pendimethalin 1.0 Kg/ha PE *fb* penoxsulam + cyhalofop-butyl (RM) 135 g/ha PoE	34565	35009	127568	142113	93003	107104	2.69	3.06
Hand weeding (HW) twice at 30 and 60 DAS	38603	40272	124848	139712	86245	99440	2.23	2.47
Partially weedy check (HW once at 60 DAS)	34103	35247	51000	63744	16897	28497	0.50	0.81

* PE =pre-emergence application; PoE = post-emergence application; DAS = days after seeding, RM = ready mix

Partially weeded check (HW once at 60 DAS) recorded maximum weed density of other weeds during both years (**Table 3**).

Economics

The maximum cost of cultivation was recorded in treatment HW twice at 30 and 60 DAS due to high labour cost and lowest cost of cultivation was recorded with penoxsulam + pendimethalin (RM) 625 g/ha PE *fb* bispyribac-sodium 25 g/ha PoE (25-30 DAS) during both years. The highest net return and B:C ratio were recorded with pendimethalin 1000 g/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE (25-30 DAS) followed by pendimethalin 1000 g/ha PE *fb* penoxsulam + cyhalofop butyl (RM) 135 g/ha PoE (25-30 DAS) and penoxsulam + pendimethalin (RM) 625 g/ha as PE *fb* fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha PoE (25-30 DAS). Although, herbicides usage increased the cost of cultivation, the increased yield compensated resulting in higher net returns. Similar results were reported by Dewangan *et al.* (2016), Dhakal *et al.* (2019), Chitale and Tiwari (2021), Yogananda *et al.* (2019).

Conclusions

It may be concluded that pendimethalin 1.0 kg/ha PE *fb* bispyribac-sodium 25 g/ha + (metsulfuron-methyl + chlorimuron-ethyl) (RM) 4 g/ha tank mix PoE at 25-30 DAS effectively managed weeds in direct-seeded rice which resulted in maximum rice growth and yield as well as maximum net return and B:C ratio.

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RESEARCH ARTICLE

Effect of conservation tillage and phosphorus levels on weed growth and wheat productivity in rice-wheat cropping system

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ABSTRACT

A field study was conducted during 2019-20 and 2020-21, to assess the effect of crops residue management, tillage and phosphorus on weeds growth and wheat productivity in rice-wheat cropping system. The weed density and biomass were significantly lower under zero-tillage (ZT) wheat grown in sequence with puddled transplanted rice (PTR) and rice residue retention as compared to rice residue removal or burning. Wheat plant height and tillers density were significantly influenced by residue management. Highest grain yield of wheat was attained in ZT-wheat with rice residue retention and in sequence with PTR with wheat residue. Wheat grain yield was 17.3 and 15.8% higher than conventional tillage-wheat without rice residue, and 12.8 and 11.7% higher in comparison to ZT-wheat grown after partial burning of rice residue, during 2019-20 and 2020-21, respectively in sequence with PTR without wheat residues. Wheat growth and yield enhanced significantly with increase in phosphorus (P) level from 0 to 60 kg/ha, across the residue management practices but weed density and biomass were unaffected. ZT-wheat with rice residue grown in sequence with PTR with wheat residues did not respond to phosphorus application and recorded similar yield with all tested doses of P. Thus, conservation tillage improved wheat productivity and reduced cultivation cost by reducing usage of fertilizers and herbicides.

Keywords: Conservation tillage, Crop residue, Phosphorus, Rice-wheat cropping system, Weed management, Wheat

INTRODUCTION

Rice-wheat system in Punjab covers 2.6 million ha with a crop residue production of 55 million tons, out of which more than 22 million tons contributed by rice (Gupta *et al.* 2020). Straw generated from wheat cultivation is removed from the combine harvested fields with the help of wheat straw combine for its utilization as animal feed. However, more than 80% of straw generated from rice fields is burned because of its low economic value, labour scarcity, interference with the sowing of subsequent crops and narrow window period before the sowing of wheat (Singh and Sidhu 2014). Heat generated from burning causes mortality of the environment friendly useful soil microbes in addition to release of green-house gases (GHG's) such as carbon dioxide (70%), carbon monoxide (7%), nitrous oxide (2.09%) and methane (0.66%) (Samra *et al.* 2003). Recent advancements in rice residue management have brought to light numerous residue management options *viz.*, surface retention of rice straw and zero-till sowing of subsequent wheat with happy seeder, mulching in other crops, *in-situ* incorporation; baling and bioenergy generation.

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Conservation agriculture (CA) with reduced or zero-tillage (ZT) reduces operational cost, energy inputs, human labour, and conserves soil and water besides addition of organic matter in soil. Addition of rice residues in wheat alters soil microclimate, microbial populations and their activity and causes subsequent nutrient transformations in soil (Kumar and Goh 2000) particularly carbon, nitrogen and phosphorus mineralization (Gupta *et al.* 2022, 2024). Further, weeds are the major threat in wheat production (Gyawali *et al.* 2022) and account for 20-40% reduction in yield (Flessner *et al*. 2021, Oerke *et al*. 2012). Crop residue cover present at soil surface affects the germination of weed seeds and emergence by altering the soil seedbank environment (Buttar *et al*. 2022). The quality and quantity of crop residue affects weed emergence and dry matter accumulation (Kaur *et al*. 2021). Retention of crop residue on the soil surface along with zero tillage has suppressive effect on weed emergence and allows the crop to gain benefit over weeds. Thus, keeping in view the advantages of conservation agriculture along with residue retention, this study was conducted to evaluate the effect of crop residues, tillage and phosphorus levels on weeds growth and wheat productivity in rice-wheat cropping system.

MATERIALS AND METHODS

A long-term field experiment was initiated in 2008 on residue management in rice-wheat system at Research Farm, Department of Agronomy, Punjab Agricultural University, Ludhiana (30°54'N, 75°48'E, 247 m average mean sea level), India. The present study was conducted during 2019-20 and 2020-21 in the same long-term experimental plot by retaining the main plots. The climate of the study site is sub-tropical and semiarid with dry and hot summer (April - June), moist weather from July - September and cool and dry winter (November to January). During cropping season (winter 2019-20), mean weekly maximum and minimum temperatures ranged from 10.3 to 35.5°C and 4.9 to 18.4°C while respective values ranged from 14.0 to 36.1°C and 3.5 to 17.9°C during 2020-21. The soil of the experimental site was sandy loam in texture (69.8% sand, 18.1% silt and 12.2% clay) with normal pH (7.16) and electrical conductivity (0.20 dS/m), low in soil organic C (0.33%) and medium in available N (285.1 kg/ha), available P (19.8 kg/ha) and available K (250.0 kg/ha). Experiment was laid out in split plot design, replicated thrice, by assigning six crop residue management practices in main plots and three phosphorus levels, *viz.* 0, 30 and 60 kg P/ha in sub plots. The main plot size was 15 m × 2.5 m and sub-plot size was10.0 m^2 (4.0 m × 2.5 m) with buffers of 0.75 m width. The details of treatments applied to rice and wheat crops grown in sequence are given in **Table 1**. In TPR WR_0-ZTW $RR_{0,}$ treatment, wheat was sown with zero till drill after removing the paddy straw. In conventional tillage treatments (TPR WR_0- CTW RR_0 and TPR WR_0–CTWRR) with and without paddy straw, the conventional seed-cum-fertilizer drill was used for wheat sowing. In TPR WR_0– ZTWRR and TPR WR-ZTWRR treatments, sowing was done in standing rice stubbles with turbo happy seeder after uniformly spreading the loose rice residue. In TPR BWR - ZTW BRR, the loose rice straw was burnt before wheat sowing in standing rice stubbles. Wheat variety, *Unnat* PBW 343 was sown in the first week of November using seed rate of 100 kg/ha with row to row spacing of 22.5 cm. Wheat crop was fertilized with phosphorus (SSP-16% P), potash (MOP-60% K) and nitrogen (Urea-46% N). The entire recommended dose of P (as per treatment) and K and 1/3rd N was applied as basal dose by broadcasting method and remaining N was applied at CRI and late tillering stages in two equal splits. Weeds were controlled by using clodinafop 60 g/ha and metsulfuron-methyl 4 g/ha after 35 days of sowing (DAS) as tank mix in 375 litres of water during both the years of study. Plant density (number of plants/ m^2) was recorded at 15 DAS from two spots in each treatment plot after complete emergence of crop. The data on weed density and biomass was recorded from each treatment at 30 (before herbicide application) and 100 DAS from two randomly selected spots with quadrat of 50 x 50 cm size. For taking biomass, weeds were removed from the ground level from the selected spots and were dried in oven at 60 ^{0}C until the constant weight. Wheat plant height was recorded at harvest and wheat tillers density at 90 DAS.Wheat grain yield was recorded from each net plot separately. Wheat root density was recorded, from different soil depth layers wise, at flowering stage. For root density, the plants were cut from the top and layer wise soil samples were taken using root sampling pipe. The sample of soil thus obtained was washed in running water in a thin nylon mesh of one mm sieve and dried in oven at 65 ^{0}C till the constant weight was attained. The root density was calculated by using the following formula

$$\text{Wheat root density (g/m}^3) = \frac{\text{Total root weight (g) in particular depth}}{\text{Total volume of soil (m}^3\text{) from which roots were collected}}$$

The data were analysed by undergoing analysis of variance (ANOVA) using CPCS1 software and the

Table 1. Details of treatments tested in rice (summer/*Kharif*) and wheat (winter/*Rabi* season) (in main plots)

Treatment	Rice	Wheat
TPR WR_0- ZTW RR_0	Transplanted puddled rice grown after complete removal of wheat residue (TPR WR_0)	Zero tillage wheat grown after complete removal of rice residue (ZTW RR_0)
TPR WR_0-CTW RR_0	Transplanted puddled rice grown after complete removal of wheat residues (TPR WR_0)	Conventional tillage wheat grown after complete removal of rice residues (CTW RR_0)
TPR WR_0-CTWRR	Transplanted puddled rice grown after complete removal of wheat residues (TPR WR_0)	Conventional tillage wheat grown with complete rice residues incorporation (CTW RR)
TPR WR_0-ZTWRR	Transplanted puddled rice grown after complete removal of wheat residues (TPR WR_0)	Zero tillage wheat grown with complete rice residues retention (ZTWRR)
TPR WR-ZTWRR	Transplanted puddled rice grown with complete retention of wheat residues (TPR WR)	Zero tillage wheat grown with complete rice residues retention (ZTWRR)
TPR BWR- ZTW BRR	Transplanted puddled rice grown after complete burning of retained wheat residues (TPR BWR)	Zero tillage wheat grown after partial burning of retained rice residues (ZTW BRR)

treatment means were compared at a significance level of 5% (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Effect on weeds

Major grassy weed in experimental field was *Phalaris minor* (11%), while the broad-leaved weeds included: *Rumex dentatus* (35%), *Medicago denticulata* (35%), *Chenopodium album* (6%), *Anagallis arvensis* (6%) and *Lepidium didymium* (7%). The crop residue management practices significantly affected the weed density and biomass (**Table 2**). In treatments where wheat was sown with happy seeder and straw was retained as mulch, significantly lower weed density and biomass was recorded as compared to residue removal/burnt or incorporation treatments. The effect of residue mulching on weed suppression was more prominent at early stages (30 DAS) as compared to late stage (100 DAS) as residue effect diminished in later stages due to its degradation with time. At 30 DAS, the weed density reduction of 35.7 and 32.5% was observed in wheat sown in rice residue retained plots followed by PTR with wheat residue (TPR WR- ZTWRR) and without wheat residue (TPR WR_0–ZTWRR) over residue removal (conventional practice, TPR WR_0-CTW RR_0), respectively. Residue retained as mulch in ZT delayed weed germination due to higher mechanical impedance and less exposure of weed seeds to solar light (Nichols *et al.* 2015). Significant reduction in weed biomass was recorded under ZT with residue retention. Similar results were also documented by Kaur *et al.* (2024), Sen *et al.* (2023) and Baghel *et al.* (2018). Weed density and biomass did not differ significantly with different phosphorus levels.

Wheat emergence and growth: Wheat sown under ZT with mulch treatments using happy seeder took a greater number of days to emerge (8-9 days) as compared to where crop was sown after preparing the seed bed (5-6 days). The overall number of plants/m^2 at 15 days was not significantly affected by residue management and phosphorus levels. Maximum tiller density was recorded at 90 DAS, thereafter; there was decline in tillers with advancement of crop age. It might be due to mortality of tillers at later stages of crop growth. Maximum plant height and tiller density was registered with treatment where residue of both crops was retained and it was significantly superior to rest of crop residue management practices. More tillers in residue retained plots as compared to conventional practice of residue removal was probably due to better soil heath, more availability of nutrients and better soil moisture (Kaur 2020, Gupta *et al.* 2022, Gupta *et al.* 2024). Taller plants and more tiller density under ZT wheat with residue retention treatments as compared to control was also reported by Kesarwani *et al.* (2017). Significant improvement in plant height and tiller density was recorded with 60 kg P/ha and lowest in control. Similar findings were also reported by Gupta *et al.* (2024), Ali *et al.* (2020) and Rafiullah *et al.* (2021). Harvest index was similar across all the treatments.

Table 2. Effect of crop residue management and phosphorus levels on weed density and biomass in wheat

Treatment	Weed density (no./m^2)				Weed biomass (g/m^2)			
	30 DAS		100 DAS		30 DAS		100 DAS	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
Crop residue management practices								
TPR WR_0- ZTW RR_0	7.64 (58.0)	7.43 (55.0)	5.28 (27.0)	5.43 (28.5)	2.50 (5.3)	2.43 (5.00)	2.09 (3.23)	2.12 (3.30)
TPR WR_0-CTW RR_0	8.75 (76.5)	8.60 (73.7)	5.70 (31.7)	5.82 (33.0)	2.67 (6.4)	2.64 (6.10)	2.15 (3.65)	2.17 (3.73)
TPR WR_0-CTWRR	9.08 (82.0)	9.01 (80.8)	6.09 (36.2)	6.19 (37.4)	2.90 (7.5)	2.83 (7.10)	2.26 (4.10)	2.28 (4.20)
TPR WR_0-ZTWRR	5.95 (35.5)	5.77 (33.0)	4.80 (22.4)	4.85 (22.7)	1.97 (2.9)	2.00 (3.09)	1.97 (2.91)	1.99 (2.96)
TPR WR-ZTWRR	5.63 (31.5)	5.52 (29.9)	4.61 (20.3)	4.85 (22.5)	1.98 (3.0)	1.92(2.75)	1.97 (2.89)	1.99 (2.98)
TPR BWR- ZTW BRR	7.86 (60.7)	7.72 (59.6)	5.26 (26.9)	5.43 (28.7)	2.55 (5.4)	2.48 (5.19)	2.11 (3.46)	2.13 (3.53)
LSD (p=0.05)	0.69	0.85	0.49	0.42	0.28	0.30	0.11	0.12
Phosphorus levels (kg/ha)								
0	7.57 (58.4)	7.40 (56.3)	5.37 (28.2)	5.47 (29.2)	2.43 (5.1)	2.37 (4.83)	2.11 (3.48)	2.13 (3.57)
30	7.36 (55.2)	7.19 (53.0)	5.17 (26.2)	5.32 (27.7)	2.39 (5.1)	2.33 (4.60)	2.09 (3.41)	2.11 (3.49)
60	7.23 (53.3)	7.03 (51.0)	5.08 (25.3)	5.33 (27.7)	2.37 (4.8)	2.31 (4.49)	2.08 (3.34)	2.10 (3.43)
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Data were subjected to square root transformation ($\sqrt{x+1}$). Original values are in parentheses.

TPR WR_0: Transplanted puddled rice (TPR) grown after complete removal of wheat residues (WR_0), TPR WR: Transplanted puddled rice (TPR) grown with complete retention of wheat residues (WR), TPR BWR: Transplanted puddled rice (TPR) grown after complete burning of wheat residues (BWR), ZTW RR_0: Zero tillage wheat (ZTW) grown after complete removal of rice residues (RR_0), CTW RR_0: Conventional tillage wheat (CTW) grown after complete removal of rice residues (RR_0), CTWRR : Conventional tillage wheat (CTW) grown with complete incorporation of rice residues (RR), ZTW RR: Zero tillage wheat (ZTW) grown with complete rice residues retention (RR), ZTW BRR: Zero tillage wheat (ZTW) grown after complete burning of rice residues (BRR).

More than 75% of roots mass was present in top soil layer (0-15 cm) irrespective of treatments. ZT treatments showed maximum root mass density than conventional practices. Maximum root mass density was found in double residue retention treatment. While, it was minimum under conventional practice. Higher root density in ZT with residue retention might be due to improvement in soil physical structure and greater retention of soil moisture which leads to better root growth. Lower root density under convention tillage sown wheat might be due to more compaction in these treatments. The compaction restricts root growth due to more resistance to root penetration (Data not given). Meena *et al.* (2015) and Mondal *et al.* (2019) also reported higher root mass densities under ZT with residue as compared to conventional tillage.

Wheat yield

Crop residue management practices and phosphorus levels caused significant variation in grain yield (**Figure 1**). The highest wheat grain yield was recorded from the plots where rice and wheat residue were retained in rice-wheat system (TPR WR-ZTWRR) which was statistically at par with treatment where rice residue was retained in wheat followed by transplanted rice without wheat residue (TPR WR_0– ZTWRR) and was significantly superior to residue removal (TPR WR_0- CTW RR_0) and burning (TPR BWR - ZTW BRR) treatments. The improvement in grain yield in TPR WR- ZTWRR was 17.3 and 15.8% and 12.8 and 11.7% over TPR WR_0-CTW RR_0 and TPR BWR - ZTW BRR during 2019-20 and 2020-21, respectively. Higher grain yield

Table 3. Effect of residue management practices and phosphorus levels on growth parameters of wheat

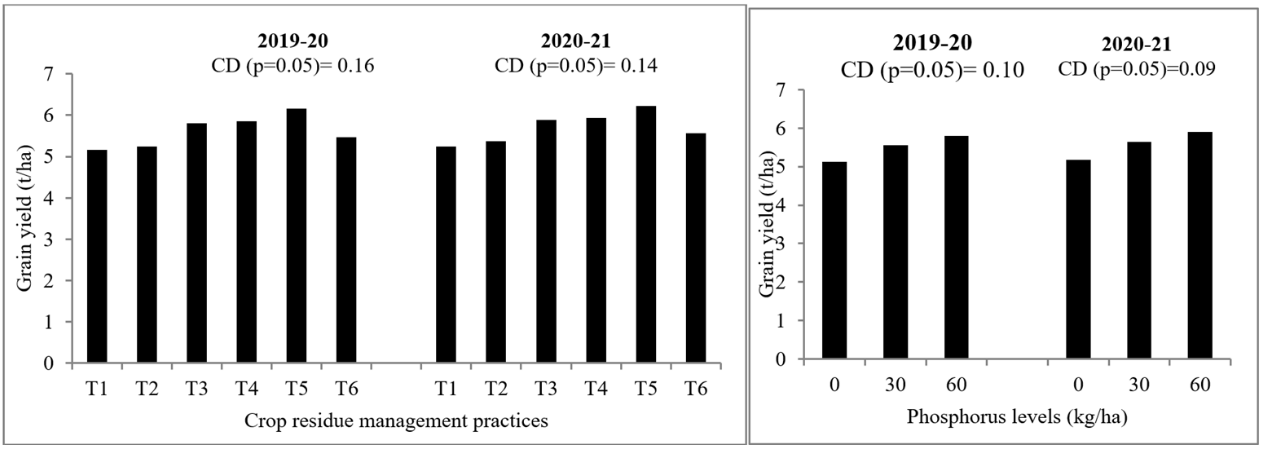
Treatment*	Days to emergence		Plant density at 15 DAS (no./m^2)		Plant height at harvest (cm)		Tiller density at 90 DAS (no./m^2)		Harvest index (%)	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
Crop residue management practices										
TPR WR_0- ZTW RR_0	7	7	155.8	164.5	75.9	77.0	364	370	42.7	42.4
TPR WR_0- CTW RR_0	5	5	164.5	172.2	76.4	79.7	366	372	42.4	42.7
TPR WR_0- CTWRR	6	6	165.0	175.2	89.1	90.9	388	395	43.8	43.1
TPR WR_0- ZTWRR	8	9	153.3	163.3	86.0	88.5	385	395	44.0	43.9
TPR WR- ZTWRR	9	8	157.3	165.2	94.4	96.6	402	410	44.2	43.6
TPR BWR - ZTW BRR	7	7	158.1	166.2	79.6	81.8	368	374	42.6	42.9
LSD (p=0.05)	-	-	NS	NS	5.2	5.3	20	17	NS	NS
Phosphorus levels (kg/ha)										
0	7	7	158.1	167.1	80.0	81.0	366	373	42.7	42.1
30	7	8	158.7	167.9	82.6	84.7	377	385	43.1	43.2
60	8	8	159.4	168.7	84.7	87.0	386	394	43.5	43.4
LSD (p=0.05)	-	-	NS	NS	2.5	2.6	8	8	NS	NS

*Refer Table 1 and 2 for details of treatments

Table 4. Effect of crops residue management and levels of phosphorus on wheat root mass density at flowering stage

Treatment*	Root mass density (g/m^3)							
	0-15 cm		15-30 cm		30-60 cm		60-90 cm	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
Crop residue management practices								
TPR WR_0- ZTW RR_0	1740	1729	370	365	163	155	113	107
TPR WR_0- CTW RR_0	1625	1621	357	352	155	146	99.0	96.0
TPR WR_0- CTWRR	1660	1664	360	359	160	151	108	103
TPR WR_0- ZTWRR	1867	1851	385	380	165	160	118	114
TPR WR- ZTWRR	1902	1895	389	385	175	168	130	124
TPR BWR - ZTW BRR	1757	1750	342	329	165	157	109	107
LSD (p=0.05)	110	92	NS	NS	NS	NS	NS	NS
Phosphorus levels (kg/ha)								
0	1680	1660	343	320	164	165	113	109
30	1765	1748	353	331	167	168	115	113
60	1823	1813	357	334	170	169.	114	115
LSD (p=0.05)	53	47	NS	NS	NS	NS	NS	NS

*Refer Table 1 and 2 for details of treatments



T1=TPR WR_0 - ZTW RR_0; T2 = TPR WR_0- CTW RR_0T3 = TPR WR_0– CTWRR; T4 = TPR WR_0– ZTWRR; T5 = TPR WR- ZTWRR; T6 = TPR BWR - ZTW BRR

Figure 1. Grain yield of wheat influenced by crop residue management practices and phosphorus levels in rice-wheat system (refer Table 1 and 2 for details of treatments)

under residue retention treatments attributed to reduction in weed density, weed biomass and better growth parameters, increase in soil organic matter content, improved soil properties (physical, chemical and biological), availability of nutrients (Sraw 2022) and more retention of soil moisture etc. which ultimately led to better plant growth and increase in grain yield (Gupta *et al.* 2024, Korav *et al.* 2024, Gupta *et al.* 2022). Interaction effect of crop residue management practices and phosphorus levels on grain yield was found to be significant during both the years of the study. ZT-wheat with rice residue plots in sequence with PTR with wheat residues did not respond to phosphorus application and resulted into similar yield with 0, 30 and 60 kg/ha phosphorus..

It was concluded that ZT wheat with rice residue retention had substantially lower weed infestation which led to significant improvement in wheat growth and grain yield.

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RESEARCH ARTICLE

Nutrients removal by weeds and wheat crop under semi-arid climate of Punjab, India

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ABSTRACT

To evaluate the nutritional losses from weed infestation in wheat crop under semi-arid climate of Punjab, a study was carried in Bathinda district of South-West Punjab. Weed infestation does not significantly influence the soil, pH, EC and organic C of the soil. The values of all nutrients were higher at farmer's field compared to research farms; event though, they belong to similar soil category as per soil fertility. The nutrients mean value was 156.6 kg N/ha, 8.9 kg P/ha, 148.9 kg K/ha and 27.2 kg S/ha for studied locations. However, the average value for N, P, K and S was 136.5, 8.3, 129 and 26.64 kg/ha, respectively under weed infested fields and 147, 8.66, 136.8 and 27.9 kg/ha under weed free fields, when compared with same location fields. Similarly, the mean value for Fe, Cu, Zn and Mn was 5.46, 0.53, 0.99 and 4.43 mg/kg, respectively under weed infested fields of surveyed area. However, slightly higher values were recorded under weed free locations (at research farm locations) with mean value of 5.44, 0.55, 0.91 and 3.97 mg/kg for Fe, Cu, Zn and Mn, respectively. Whereas the mean value at the research farm locations was 5.41, 0.53, 0.88 and 3.91 mg/kg for Fe, Cu, Zn and Mn under weed infested fields.

Keywords: Nutrients removal, Weeds, Wheat, Semi-arid region, Soil nutrient status

INTRODUCTION

About 20% of the world's dietary calorie and protein intake comes from wheat (*Triticum aestivum* L.), a staple crop that contributes to global food security (Gooding and Shewry 2022). The wheat produced worldwide was over 793 million metric tons in 2024–2025 (Statista 2025) and in India 1132.92 lakh tons of wheat was produced from 318.33 lakh hectares area in 2023–2024 with wheat productivity of 3.56 t/ha (GOI 2025). In Punjab, 165.67 lakh tons of wheat was produced during 2022–2023, on an area of 35.17 lakh hectares, with an average productivity of 4.71 t/ha (Anonymous 2024). Both biotic (weeds, insects, pathogens, *etc*.) and abiotic (heat, drought, salt, *etc*.) factors contribute to the low wheat productivity and weeds are one of the main constraints (Walia 2006, Oerke *et al*. 2012, Singh *et al*. 2015). Wheat is infested by grassy and broad-leaved weeds and sedges. According to numerous studies, the amount of wheat yield lost due to weeds can vary from 16 to 60%, depending on the type of weed, its severity, the length of the infestation, the crop plant ability to compete under various agro-ecological conditions (Rao *et al*. 2014, Yaduraju *et al*. 2015). Actual economic losses due to weeds in wheat were estimated, in India, as USD 3376 million (Gharde *et al*. 2018). However, little is known about the nutrient losses caused by various weed infestations in the area throughout the wheat growing phase. Hence, this study was conducted with an objective to evaluate the nutritional losses resulting from weed infestation in the wheat crop for which a survey was carried out during *Rabi* 2024-25, gathering samples of soil, wheat and weeds from the farmer's fields and research farms of the Punjab Agricultural University, Regional Research Station, Bathinda.

MATERIALS AND METHODS

The field survey was carried out in March 2025 during which collection was done of soil samples, weeds, and wheat plants from fields infested with weeds and fields free of weeds in Bathinda district of Punjab (**Table 1**). A total of 40 soil samples, 30 weed samples of 5 common species, 10 and 30 wheat samples from weed free and weed infested fields were collected from eight locations of three blocks in the district. The commonly found weeds in the surveyed fields were *Cyperus iria* Linn., *Heliotropium eichwaldi* Steud. ex. DC, *Trigonella polycerata* Linn., *Parthenium hysterophorus* Linn., *Phalaris minor* Retz. and *Chenopodium album* Linn.

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Table 1. Details of locations of field survey and the samples collection

Site number	Site name and locations	Number of soil and plant samples collected			
		Soil samples	WWFF	WWIF	Common weed species
1	**Research Farm RRS, Bathinda** 30°11'23.8"N 74°56'53.6"E, 30°11'25.5"N 74°57'08.2"E, 30°11'18.1"N 74°56'45.7"E, 30°11'16.7"N 74°56'47.2"E, 30°11'15.6"N 74°56'47.4"E	5	-	5	5
2	**Research Farm RRS, Bathinda (weed free field)** 30°11'31.2"N 74°56'50.1"E, 30°11'23.8"N 74°56'55.1"E, 30°11'25.0"N 74°56'56.3"E, 30°11'26.0"N 74°56'53.6"E, 30°11'22.6"N 74°56'51.6"E	5	5	-	-
3	**Sekhpura farmers field, Bathinda** 29°59'38.7"N 75°09'40.6"E,29°59'49.4"N 75°09'02.4"E, 29°59'47.2"N 75°09'07.2"E, 29°59'49.7"N 75°09'14.8"E, 29°59'40.1"N 75°09'14.1"E	5	-	5	5
4	**Sekhpura Seed Farm RRS, Bathinda (weed free field)** 29°59'21.7"N 75°07'43.5"E,29°59'26.7"N 75°07'42.8"E,29°59'31.1"N 75°07'46.4"E, 29°59'27.6"N 75°07'47.5"E, 29°59'30.0"N 75°07'52.0"E	5	5	-	-
5	**Jai Singh Wala** 30°08'02.8"N 74°51'39.4"E,30°08'22.9"N 74°52'02.9"E,30°08'17.7"N 74°51'59.9"E, 30°08'17.5"N 74°51'59.8"E, 30°08'19.9"N 74°52'06.4"E	5	-	5	5
6	**Katar Singh Wala** 30°08'46.3"N 74°59'39.9"E,30°08'37.3"N 74°59'47.1"E,30°08'34.2"N 74°59'41.1"E, 30°08'32.6"N 74°59'40.5"E, 30°08'38.2"N 74°59'48.1"E	5	-	5	5
7	**Jassi Pauwali** 30°08'58.8"N74°58'18.0"E,30°08'59.1"N 74°58'03.1"E,30°08'51.5"N 74°58'06.2"E, 30°08'58.6"N 74°58'17.0"E, 30°09'01.7"N 74°58'09.7"E	5	-	5	5
8	**Jodhpur Romana** 30°09'13.1"N 74°56'56.0"E,30°09'18.1"N 74°56'42.6"E,30°09'21.3"N 74°56'39.3"E, 30°08'53.8"N 74°55'36.2"E, 30°08'53.6"N 74°54'56.9"E	5	-	5	5
	Total samples	40	10	30	30

WWFF-Wheat plant from weed free field, WWIF- Wheat plant from weed infested field (as farmers field weed infestations were varied according to management practices adopted by the farmers, only commonly occurring weed plants were considered during the study).

After the soil was air dried, the soil samples were sieved using a 2 mm mesh sieve and placed in polythene bags for further examination. The methods outlined by Jackson (1973) was used to measure the pH and electrical conductivity (EC) of soil in a 1:2 soil-water solution by pH meter and an electrical conductivity meter. The wet digestion method created by Walkley and Black (1934) was used to measure the soil organic carbon. The standard approach of Subbiah and Asija (1956) was used to analyze the amount of available nitrogen. Available potassium (K) was determined using the method described by Rowell (1994), and available phosphorus (P) was determined using the conventional procedure of Olsen *et al.* (1954). Using an atomic absorption spectrophotometer (Varian Model AAS FS 240), the DTPA extractable micro-nutrients (Zn, Fe, Mn, and Cu) were analysed using the procedures described by Lindsay and Norvel (1978).

To remove soil and other impurities, collected plant samples were carefully cleaned with distilled water and allowed to dry for three hours in the shade. After three hours, the samples were weighed, were dried in an oven at 60 ± 5°C until constant weight. The plants dry weight was noted, ground in a Willey mill, and then kept for nutrients analysis. To analyze the nutrients content in plants the standard methods outlined by Piper (2011) were used. The nutrient uptake by plants was calculated as follow:

Macro-nutrient uptake (g/plant) = [Dry matter (g) × Nutrient content (%)]/100

Micro-nutrient uptake (mg/plant) = [Dry matter (g) × Nutrient content (mg/kg)]/1000

The data was subjected to statistical analysis using MS Excel 2007 package.

RESULTS AND DISCUSSION

Soil parameters of the sampling sites

The soil pH, EC and OC of the soil had no significant influence on weed infestation (**Table 2**). However, the pH value varied from 8.1-8.5 at RRS, Bathinda, 8.1-8.5 at Sekhpura, 8.2-9.3 at Jai Singh Wala, 8.2-9.7 at Katar Singh Wala, 8.4-8.7 at Jassi Pauwali and 8.3-9.7 at Jodhpur Romana with average value of 8.26, 8.35, 8.72, 8.66, 8.58 and 8.88, respectively. Yadav *et al.* (2018) observed neutral to alkaline pH in soil of Bathinda district. Further, Yadav (2020) reported that the 0-15 cm soil pH ranged 8.01-9.80 with mean of 8.85 in the cotton-wheat cropping system in Sangat block of Bathinda district as reported earlier by Kalhon *et al.* (2021) and Yadav *et al.* (2023). The soil EC ranged from 0.21-0.29 dS/m with average value of 0.25 dS/m; 0.24-0.35 dS/m; 0.29 dS/m; 0.18-0.45 dS/m; 0.30 dS/m; 0.26-0.52 dS/m; 0.37 dS/m; 0.33-0.45 dS/m; 0.40 dS/m; 0.18-0.48 dS/m; 0.37 dS/m at RRS, Bathinda; Sekhpura; Jai Singh Wala; Katar Singh Wala; Jassi Pauwali and Jodhpur Romana, respectively. The higher soil EC (0.40 dS/m) was recorded at Jassi Pauwali followed by Katar Singh Wala and Jodhpur Romana with average value of 0.37 dS/m compared to other locations. The lower values of electrical conductivity in soils may be attributed to more macro pores, as majority of the soil samples in the area are light textured, resulting in free drainage conditions. The earlier reported EC of arid soils in the Bathinda district, ranged from 0.11-0.18 dS/m in sand-dunes, 0.19-0.27 dS/m in inter dunal soils, and 0.20-0.31 dS/m in alluvial terrace soils, indicating their non-saline nature (Singh and Sharma 2013). Yadav *et al.* (2018)

based on analysis of 2506 soil samples from the Bathinda district found that 85% of the samples were in the normal range (EC <0.8 dS/m) and 15% of the samples had EC > 0.8 dS/m. Further, Yadav (2020), Kalhon *et al.* (2021) and Yadav *et al.* (2023) reported the similar results.

The data of soil pH, EC, OC and macro-nutrients revealed that the soil organic carbon (OC) ranged from 0.23-0.56% with average value of 0.40%, observing higher value of 0.51% at Sekhpura followed by 0.42% at Jassi Pauwali and 0.40% at Jodhpur Romana (**Table 2**). The medium to higher organic carbon content in the soils may be attributed to the proper vegetation, avoiding crop residue burning and incorporation into the soil.

Singh and Sharma (2013) reported about 0.22 %, 0.31% and 0.34% organic carbon in surface horizon of sand dunes, inter dunal and alluvial terraces soils of Bathinda. Yadav *et al.* (2018) observed mean value of OC varied between 0.31 to 0.62% in different blocks of Bathinda and showed that 61 to 70% samples were deficient in organic carbon. Similar results were also reported by Yadav (2020), Kalhon *et al.* (2021) and Yadav *et al.* (2023) in soil of Bathinda district under various cropping system. The weeds infested fields significantly had low amount of macro and micro-nutrient (N, P, K, S and Fe, Cu, Zn and Mn) compared to weed control/ weed free fields, however the amount of nutrients varied according to sampling site and agronomic management during the crop (**Table 2** and **3)**. The value of all nutrients was higher at farmer's fields compared to research farm; however, they belong to similar soil category as per soil fertility. The nutrients value ranged from 125-148 kg N/ha, 7.4-8.9 kg P/ha, 121-138 kg K/ha and 22.4-32.4 kg S/ha with mean value of 136.5, 8.3, 129 and 26.64 kg/ha under weed infested fields, whereas, it ranged from 140-155 kg N/ha, 7.6-9.3 kg P/ha, 128-147 kg K/ha and 23.4-33.5 kg S/ha with mean value of 147, 8.66, 136.8 and 27.9 kg/ha under weed free fields, when compared with same location fields. However, the nutrients ranged from 125-174 kg/ha with mean value of 156.6 kg N/ha, 7.4-10.8 kg/ha with mean value of 8.9 kg P/ha, 121-201 kg/ha with mean value of 148.9 kg K/ha and 21.5-35.2 kg/ha with mean value of 27.2 kg S/ha in the studied locations. It was also recorded that the macro-nutrient (N, P, K and S) values were higher at farmers fields compared to research farms, may be due to use of higher dose of fertilizers by the farmers than recommended dose for the crops.

Similarly, the micro-nutrients value (**Table 3**) ranged from 4.68-6.42 mg/kg for Fe, 0.35-0.85 mg/kg for Cu, 0.67-1.32 mg/kg for Zn and 3.75-6.05 mg/kg for Mn with mean value of 5.46, 0.53, 0.99 and 4.43 mg/kg under weed infested fields of surveyed area, respectively. However, slightly higher values were recorded under weed free locations (at research locations) and values ranged from 4.68-6.19 mg/kg for Fe, 0.38-0.78 mg/kg for Cu, 0.68-1.14 mg/kg for Zn and 3.79-4.12 mg/kg for Mn with mean value of 5.44, 0.55, 0.91 and 3.97 mg/kg under weed free fields. Whereas the corresponding values at the research location ranged from 4.68-6.15 mg/kg for Fe, 0.35-0.75 mg/kg for Cu, 0.67-1.12 mg/kg for Zn and 3.75-4.09 mg/kg for Mn with mean value of 5.41, 0.53, 0.88 and 3.91 mg/kg under weed infested fields.

The micro-nutrient (Fe, Cu, Zn and Mn) values were higher at farmers' fields, may be due to soil application of micro-nutrients fertilizers by the farmers for different crops over the years. Whereas the nutrients values were comparatively low at

Table 2. Range and mean value of soil pH, EC, OC and macro-nutrients of the surveyed fields

Site name*	Soil $pH_{1:2}$	Soil $EC_{1:2}$ (dS/m)	Soil OC (%)	Soil N (kg/ha)	Soil P (kg/ha)	Soil K (kg/ha)	Soil S (kg/ha)
Research Farm RRS, Bathinda	8.1-8.4 (8.2±0.05)	0.21-0.29 (0.25±0.01)	0.38-0.45 (0.40±0.01)	125-135 (130±1.99)	7.40-8.70 (8.20±0.22)	121-132 (126±1.87)	23.4-28.4 (25.6±.84)
Research Farm RRS, Bathinda (weed free field)	8.1-8.5 (8.3±0.07)	0.22-0.29 (0.25±0.01)	0.34-0.38 (0.36±0.01)	140-148 (144±1.36)	7.60-9.20 (8.58±0.27)	128-137 (131±1.64)	24.9-29.8 (27.4±0.84)
Sekhpura farmers field, Bathinda	8.1-8.5 (8.4±0.07)	0.24-0.35 (0.28±0.02)	0.47-0.56 (0.50±0.02)	138-148 (143±1.78)	8.20-8.90 (8.54±0.13)	125-138 (133±2.67)	22.4-32.4 (27.4±1.60)
Sekhpura Seed Farm RRS, Bathinda (weed free field)	8.2-8.5 (8.3±0.06)	0.25-0.34 (0.29±0.02)	0.45-0.56 (0.51±0.02)	145-155 (150±1.71)	8.60-9.30 (8.98±0.12)	135-147 (142±2.24)	23.4-33.5 (28.7±1.68)
Jai Singh Wala	8.2-9.3 (8.7±0.21)	0.18-0.45 (0.30±0.04)	0.23-0.36 (0.28±0.03)	159-171 (165±2.12)	8.30-9.40 (8.80±0.22)	139-165 (150±4.69)	22.4-32.4 (27.2±1.71)
Katar Singh Wala	8.2-9.7 (8.7±0.27)	0.26-0.52 (0.37±0.04)	0.26-0.36 (0.32±0.02)	165-174 (169±1.83)	8.50-9.60 (9.18±0.19)	143-165 (154±4.37)	21.5-32.1 (27.0±1.89)
Jassi Pauwali	8.4- 8.7 (8.6±0.05)	0.33-0.45 (0.40±0.02)	0.34-0.52 (0.42±0.03)	159-175 (165±2.60)	8.30-9.20 (8.84±0.18)	129-165 (143±6.14)	21.5-32.1 (27.0±1.81)
Jodhpur Romana	8.3-9.7 (8.9±0.27)	0.18-0.18 (0.37±0.05)	0.26-0.52 (0.40±0.04)	158-173 (167±2.63)	8.90-10.80 (9.88±0.31)	166-201 (188±6.07)	22.5-35.2 (29.0±2.15)

Values in parentheses denoted the mean± SEM;* Refer table 1 for details research farms due to use of recommended dose of micro- nutrients fertilizers usually top-dressed through sprays. Global warming, soil, and agricultural practices (*e.g.* tillage, irrigation, and fertilization) have varying potential to affect the abundance and diversity of weed species (Travlos *et al.* 2018) and soil nutrient content.

Punjab state alone consumes 9% of the total fertilizers in India and the use is the highest on per unit area basis at 190.0 kg/ha of the gross cropped area against 88.2 kg/ha in all India. Farmers applied more chemical fertilizers than recommended to raise productivity of high yielding varieties due to higher responsiveness (Anonymous 2025). Earlier, Arora (2020) noted that the imbalanced use of fertilisers in India is evident from the fact that the desirable ratio of N: P: K application is 4:2:1 at national level, while it is 31.4:8:1 in Punjab.

Plant weight, nutrients content and uptake by weeds and crop

The fresh and dry weight of plants and their macro and micro-nutrients content (**Table 4**) revealing that *Chenopodium album* had the maximum weight/plant as compared to wheat plant in both conditions (collected from weed infested and weed free field).

Chenopodium album had higher moisture (12%) as compared to wheat (11%) under weed infested fields while moisture content was 15 % for wheat plant under weed free field at the sampling period. Tehmina and Rukhsana (2010) found that *Chenopodium album* caused a 41.6% decrease in tillering of wheat due to competition for water, nutrients, and light with wheat was drastic reduction in the total dry matter content of wheat. The consumptive use of water of a common weed *Chenopodium album* was 550 mm as against 479 mm for wheat since weed can remove moisture from deeper depths of soil than crops (Hasanuzzaman 2015).

Irrespective of weed species macro-nutrient content in weed plants ranged from 1.1-1.8 % for N, 0.42-0.49% for P, 1.85-8.43% for K and 0.73-0.83% for S with mean of 1.30% N, 0.46% P, 2.36% K and 0.75% S. However, the wheat plant from weed infested field contained N by 1.2-1.6%, P by 0.53-0.59%, K by 2.0—2.8% and S by 0.88-0.95% with mean value of 1.4%, 0.56%, 2.4% and 0.91%, whereas, wheat plant from weed free field contained 1.5-1.6% N with mean value of 1.6%, 0.63-0.65% P with mean value of 0.64%, 2.5-2.8% K with mean value of 2.6% and 0.99-1.01% S with mean value of

Table 3. Range and mean value of soil micro-nutrients of the surveyed fields

Site name*	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)
Research Farm RRS, Bathinda	4.68-5.65(5.13±0.16)	0.35-0.56(0.46±0.04)	0.67-0.95(0.77±0.05)	3.78-4.01(3.89±0.04)
Research Farm RRS, Bathinda (weed free field)	4.68-5.66(5.17±0.16)	0.38-0.58(0.48±0.04)	0.68-1.01(0.79±0.06)	3.88-4.09(3.95±0.04)
Sekhpura farmers field, Bathinda	5.16-6.15(5.57±0.20)	0.45-0.75(0.60±0.05)	0.78-1.11(0.99±0.06)	3.75-4.09(3.93±0.06)
Sekhpura Seed Farm RRS, Bathinda (weed free field)	5.22-6.19(5.61±0.20)	0.46-0.78(0.62±0.05)	0.79-1.14(1.03±0.07)	3.79-4.123.97±0.06)
Jai Singh Wala	5.06-5.42(5.26±0.06)	0.35-0.48(0.40±0.02)	0.88-1.24(1.05±0.06)	3.76-4.15(4.03±0.07)
Katar Singh Wala	4.75-5.48(5.07±0.13)	0.42-0.83(0.53±0.08)	0.98-1.32(1.16±0.06)	4.05-5.15(4.49±0.22)
Jassi Pauwali	5.09-6.42(5.63±0.27)	0.38-0.55(0.47±0.03)	0.86-1.14(1.02±0.05)	5.15-6.05(5.70±0.19)
Jodhpur Romana	5.35-6.25(5.87±0.16)	0.38-0.85(0.56±0.09)	0.75-1.22(0.96±0.08)	4.15-5.01(4.51±0.16)

Values in parentheses denoted the mean± SEM;* Refer table 1 for details

Table 4. Range and mean value of different plant parameters of the weeds and wheat per plant collected during the study period

Plant species	Fresh weight (g)	Dry weight (g)	N (%)	P (%)	K (%)	S (%)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)
Cyperus iria Linn.	1.2-1.6 (1.5±0.05)	0.21-0.29 (0.23±0.01)	1.2-1.3 (1.2±0.02)	0.43-0.48 (0.46±0.01)	2.0-2.1 (2.1±0.03)	0.73-0.81 (0.78±0.01)	30.4-34.2 (32.9±0.70)	7.3-7.9 (7.6±0.10)	16.2-17.7 (17.0±0.23)	21.4-23.4 (22.3±0.29)
Heliotropium eichwaldi Steud. ex. DC	3.4-3.8 (3.7±0.06)	0.93-1.28 (1.08±0.06)	1.2-1.3 (1.3±0.02)	0.44-0.48 (0.46±0.01)	2.0-2.3 (2.2±1.03)	0.71-0.83 (0.76±0.02)	31.8-35.4 (33.6±0.47)	7.0-8.0 (7.4±0.14)	16.1-18.7 (17.1±0.44)	21.4-23.8 (22.6±0.38)
Trigonella polycerate Linn.	13.4-15.0 (14.4±0.23)	3.9-5.0 (4.4±0.19)	1.2-1.5 (1.3±0.05)	0.46-0.49 (0.47±0.01)	2.0-8.4 (3.3±1.03)	0.70-0.82 (0.74±0.02)	33.3-40.9 (35.9±0.37)	6.7-7.9 (7.5±0.17)	16.5-18.0 (17.0±0.22)	22.6-24.7 (23.6±0.36)
Parthenium hysterophorus Linn.	45.3-50.6 (48.7±0.78)	13.3-17.0 (14.8±0.63)	1.2-1.7 (1.4±0.08)	0.43-0.48 (0.46±0.01)	1.9-3.0 (2.3±0.15)	0.70-0.81 (0.75±0.02)	32.5-35.4 (34.8±0.46)	6.8-8.2 (7.4±0.22)	15.5-19.0 (17.7±0.53)	19.8-23.7 (22.3±0.63)
Phalaris minor Retz.	17.1-19.1 (18.3±0.29)	5.0-6.4 (5.6±0.24)	1.1-1.8 (1.3±0.10)	0.42-0.48 (0.46±0.01)	1.8-3.0 (2.2±0.17)	0.70-0.77 (0.73±0.01)	34.7-41.2 (37.1±1.17)	7.2-7.6 (7.3±0.05)	17.1-19.2 (18.2±0.32)	22.0-24.5 (23.1±0.36)
Chenopodium album Linn.	476.3-532.2 (512.1±8.22)	411.4-535.1 (457.5±22.0)	1.1 -1.7 (1.3±0.09)	0.43-0.46 (0.45±0.01)	1.9-2.9 (2.1±0.16)	0.70-0.78 (0.74±0.01)	32.9-41.7 (37.4±1.47)	6.9-7.6 (7.2±0.12)	16.7-18.7 (17.5±0.30)	21.0-24.0 (23.0±0.45)
Triticum aestivum-weed infested field	105.3-117.7 (113.2±1.82)	92.7-118.3 (101.8±4.61)	1.2-1.6 (1.4±0.07)	0.53-0.59 (0.56±0.01)	2.0-2.8 (2.4±0.12)	0.88-0.95 (0.91±0.01)	48.0-49.3 (48.5±0.18)	9.2-9.9 (9.6±0.11)	21.9-22.9 (22.6±0.16)	27.4-29.2 (28.3±0.25)
Triticum aestivum- weed free field	112.0-118.8 (115.4±1.94)	98.6-100.9 (99.8±0.68)	1.5-1.6 (1.6±0.03)	0.63-0.65 (0.64±0.01)	2.5-2.8 (2.6±0.08)	0.99-1.01 (0.99±0.01)	50.4-50.6 (50.5±0.07)	9.5-10.2 (9.9±0.20)	23.2-23.5 (23.3±0.08)	28.4-28.5 (28.4±0.02)

Values in parentheses denoted the Mean± SEM

0.99%, which was higher than wheat from weed infested field and weeds. Likewise, micro-nutrients in weed plants ranged from 30.25- 41.69 mg/kg with mean of 35.28 mg/kg for Fe, 6.73-8.17 mg/kg with mean of 7.40 mg/kg for Cu, 15.53-19.17 mg/kg with mean of 17.40 mg/kg for Zn and 19.77- 24.67 mg/kg with mean of 22.82 mg/kg for Mn. The wheat plant from weed infested field contained 48.0-49.3 mg/kg Fe, 9.2-9.9 mg/kg Cu, 21.9-22.9 mg/kg Zn and 27.4-29.2 mg/kg Mn. While wheat plant from weed free field contained 50.4-50.6 mg/kg Fe with mean value of 50.5 mg/kg, 9.5-10.2 mg/kg Cu with mean value of 9.9 mg/kg, 23.2-23.5 mg/kg Zn with mean value of 23.3 mg/kg and 28.4-28.5 mg/kg Mn with mean value of 28.4 mg/kg which was higher than weeds and wheat from weed infested field. The weed infestation reduced the nutrients content by 9.0 % N, 12.3% P, 10.1% K and 8.4% S and Fe, Cu, Zn and Mn by 4.0%, 2.9%, 3.0% and 0.4 % in wheat plants. Different plant species have a variable response to nutrient content because of crop-weed competition and fertility status of the fields.

Macro and micro-nutrients uptake by different plant species as analysed during the study (**Figure 1)** indicated the maximum plant uptake for macro-nutrients (N, P, K and S) by *Chenopodium album* Linn (5.87, 2.05, 9.83 and 33.81 g/plant) followed by *Parthenium hysterophorus* Linn (0.20, 0.07, 0.34 and 1.11 g/plant) and *Phalaris minor* Retz. (0.07, 0.03, 0.12 and 0.41 g/plant). The N, P, K and S uptake by wheat from weed free and weed infested fields were recorded by 1.55 and 1.44, 0.64 and 0.57, 2.62 and 2.40, 9.89 and 9.25 gm/plant (**Figure 1A**). Higher Fe, Cu, Zn and Mn uptake was observed by *Chenopodium album* Linn (0.51, 0.11, 0.26 and 0.33 µg/plant) followed by *Parthenium hysterophorus* Linn (0.51, 0.11, 0.26 and 0.33 µg/plant) and *Phalaris minor* Retz. (0.21, 0.04, 0.10 and 0.13 µg/plant). The Fe, Cu, Zn and Mn uptake by wheat from weed infested and weed free fields were recorded by 4.94 and 5.04, 0.97 and 0.98, 2.30 and 2.33, 2.84 and 2.88 µg/plant (**Figure 1B**).

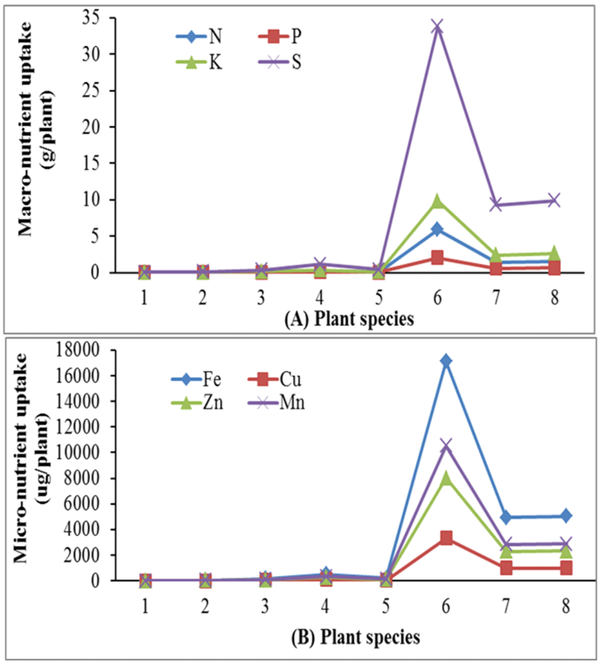

Figure 1. Macro and micro-nutrients uptake by different plant species collected during the study

Plant species 1. *Cyperusiria* Linn.; 2. *Heliotropium eichwaldi* Steud. ex. DC; 3. *Trigonella polycerata* Linn.; 4. *Parthenium hysterophorus* Linn.; 5. *Phalaris minor* Retz.; 6. *Chenopodium album* Linn.; 7. *Triticum aestivum*-weed infested field; 8. *Triticum aestivum*- weed free field.

Higher Fe, Cu, Zn and Mn uptake was observed by *Chenopodium album* Linn (0.51, 0.11, 0.26 and 0.33 µg/plant) followed by *Parthenium hysterophorus* Linn (0.51, 0.11, 0.26 and 0.33 µg/plant) and *Phalaris minor* Retz. (0.21, 0.04, 0.10 and 0.13 µg/plant). The Fe, Cu, Zn and Mn uptake by wheat from weed infested was 4.94 and 5.04, 0.97, respectively and weed free fields were 0.98, 2.30 and 2.33, 2.84 and 2.88 µg/plant (**Figure 1B**), respectively. The weed infestation decreased the N, P, K and S uptake of wheat by 7.1, 10.4, 8.2 and 6.5 %, respectively (**Figure 2A**) and decrease the Fe, Cu, Zn and Mn uptake of wheat by 2.0, 0.8, 1.0 and 1.6%, respectively (**Figure 2B**) due to weed infestation. Nutrient uptake by crops is primarily a function of yield and nutrient content. A weedy crop resulted in the least nutrient uptake. Poor growth and

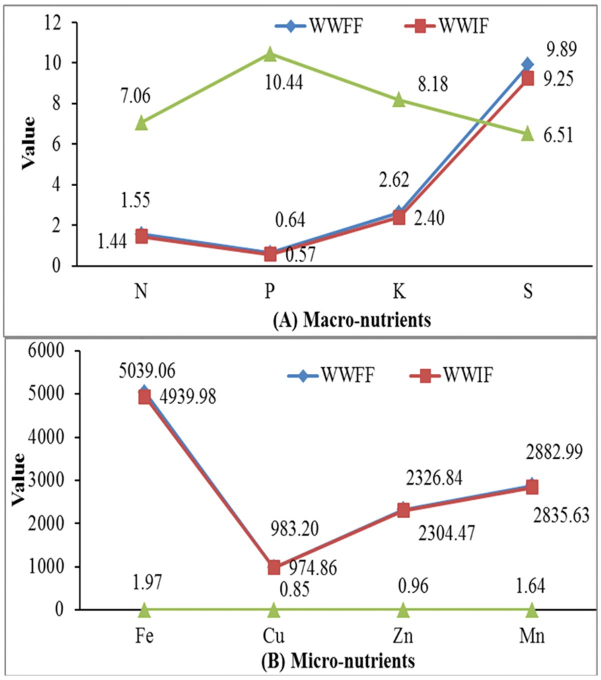

Figure 2. Percent decrease in nutrients uptake by wheat plant due to weeds infestation

(WWFF- Wheat plant from weed free field, WWIF- Wheat plant from weed infested field) low uptake of nutrients by wheat in weedy field might be due to less photosynthates, then less assimilates to numerous metabolic sinks and ultimately poor development of yield components (Shivran *et al.* 2020). Abouziena *et al.* **(**2008) reported that an N content of wheat was decreased by 2.7% due to weed infestation.

Conclusions

It could be concluded that weed infestation does not significantly influence the soil, pH, EC and organic C of the soil. However, weeds infested fields had significantly low amount of macro (N, P, K, and S) and micro-nutrient (Fe, Cu, Zn and Mn) compared to weed free fields. The weed infestation decreased the macro and micro-nutrients uptake by wheat and it varied with infested weed species, intensity of weed infestation, soil fertility status and crop cultivation practices used.

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RESEARCH ARTICLE

Evaluation of different planting methods and herbicides for weed management in maize and their residual effect on succeeding wheat crop

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ABSTRACT

Maize (*Zea mays* L.) production is affected by severe weed infestation due to frequent rainfall during wet season (*Kharif*) and inadequate interculture practices adoption by farmers. Thus, alternative integrated weed management practices need to be developed for effective management of weeds in maize. Hence, an experiment was conducted, during 2020-21 and 2021-22, using strip plot design with ten planting methods in main plots and four weed control treatments in sub plots. Greater grassy, broad-leaved and sedges density reduction along with maximum wheat and maize yield was observed with the raised bed wide bed planting with paddy residue (6 t/ha) *fb* zero till (ZT) wheat reshaping of beds, compared to sowing of maize with pneumatic planter without residues *fb* ZT wheat which had maximum density of all types of weeds. Surface mulching of paddy residue and sowing of maize on raised bed wide bed planting *fb* ZT wheat reshaping of beds reduced grassy (86.0-89.0%), broad-leaved weeds (44.8-50.8%) and sedges (80.2-83.5%) density significantly as compared to the same planting methods without surface mulching. The higher reduction in weed biomass of grassy (79.3-80.7%), broad-leaved weeds (82.4-84.1%) and sedges (82.7-87.8%), in comparison to weedy check, was recorded with tembotrione 120 g/ha. Tembotrione 120 g/ha PoE at 15 DAS recorded the highest gross returns, net returns and highest B:C ratio, due to the lowest cost of cultivation, during both years of study.

Keywords: Economics, Maize-wheat cropping system, Pneumatic planter, Ridge sowing, Tembotrione, Topramezone, Weed management

INTRODUCTION

Maize (*Zea mays* L.) is an important crop grown under wider agroecological conditions and considered as potential drivers of crop diversification. With an area of over 1.8 million ha, maize-wheat cropping system is the third most important cropping system in India, after rice-wheat and rice-rice, and contributes about 3% to the country's food basket. Maize has the largest genetic yield potential among cereal crops. It is grown on 205.9 million hectares of land worldwide, producing 1210.2 million tons of grain with an average yield of 5.88 t/ha. In India, maize is the third most significant cereal crop, after rice and wheat, with a 9.9-million-hectares area, 31.7 million tons of production, and an average grain yield of 3.12 t/ha (Anonymous 2024a). In Haryana, the *Kharif* season's maize acreage is approximately 9300 ha, with production of roughly 28000 tons and an average productivity of 3.01 t/ha (Anonymous 2024b).

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Weeds are the important limiting factor causing significant yield losses in crops. Agronomic practices, such as tillage (Wasnik *et al.* 2022), establishment methods (Khedwal *et al.* 2023), sowing time, surface mulching (Khedwal *et al.* 2017) etc. also influence the weeds infestation. The residue retention was reported to lower density and reduced biomass of all type of weeds under different methods of maize planting (Khedwal et a. 2017). Use of rice straw mulch at 9.00 t/ha produced significantly lower weed biomass as compared to 6.25 t/ha rice straw mulch and no mulch treatments (Kaur *et al.* 2020) as straw mulch alters the microclimatic conditions of the soil surface, which in turn affects the weed spectrum (Ghimire *et al.* 2017). Mulch reduces the quantity of solar radiation available, which inhibits the growth of undesirable weeds.

Among the herbicidal treatments in maize, tembotrione at 120 g/ha registered the lowest density and biomass of grassy weeds, broad-leaved weeds and sedges (Sharma *et al.* 2018). The higher weed control efficiency with post-emergence application (PoE) of topramezone + atrazine 25.2 + 250 g/ha and tembotrione + atrazine 105 + 250 g/ha was reported earlier (Swetha *et al.* 2018). However, limited studies are available on interactive effect of planting methods, surface mulching and herbicides against weeds in maize and succeeding wheat. Hence, this study was conducted with an objective to evaluate the efficacy of planting methods, paddy residue mulching and herbicides in managing weeds and improving productivity of maize and succeeding wheat.

MATERIALS AND METHODS

Experimental site and design

The experiment was conducted at Regional Research Station, Karnal of CCS Haryana Agricultural University, Hisar during 2020-21and 2021-22. The experiment was laid out in strip plot design with ten planting methods (**Table 1**) and four weed control treatments and replicated thrice. The cropping system was initiated with maize in *Kharif* 2020. The strip plot treatments were fixed in same plots for two years study. The plots were prepared as per treatments *i.e*. two harrowing + two ploughings followed by planking as preparatory tillage for the ridge sowing with dibbling method, multi crop ridge planter, pneumatic maize planter and raised bed wide bed planter whereas in zero tillage treatment, no tillage operation was carried out during the first-year crop of maize.

The herbicide treatments, in sub plots, were: weed free check, weedy check, post-emergence application (PoE) of tembotrione 120 g/ha and topramezone 25.2 g/ha PoE. The herbicides were applied by the knapsack sprayer fitted with flat fan nozzle with water volume 375 l/ha at 15 days after sowing (DAS). In wheat cropping season *i.e*., two harrowing + two ploughings followed by planking were done as preparatory tillage for conventional sowing of wheat crop in the ridge sowing with dibbling method and multi crop ridge planter, whereas in raised bed wide bed planting method the reshaping of beds done as permanent beds; in zero tillage treatment and pneumatic maize planter treatment, no tillage operations were carried out first year wheat crop season. The seed bed was prepared after applying pre-sowing irrigation as per the treatments. Single cross maize hybrid HQPM 1 and wheat variety HD 2967 was used for sowing. Ridger, multi crop ridge planter, raised bed wide bed planter, pneumatic maize planter and zero-till seed-cum-fertilizer drill was used for sowing of maize crop with row-to-row distance of 60 cm and plant to plant 20 cm. For wheat crop sowing zero-till seed-cum-fertilizer drill was used for sowing across conventional and zero tillage plots keeping row to row distance of 20 cm. The sowing of wheat crop was done on raised bed wide bed planter with reshaping of bed and keeping the row-to-row distance 20 cm on bed.

Crop management

Recommended seed rate of 25 kg/ha for maize and 100 kg/ha for wheat was used for sowing. The maize crop was sown on 3rd and 6th July during *Kharif* 2020 and 2021 and wheat crop was sown on 17th and 11th November during *Rabi* 2020-21 and 2021-22, respectively. In maize crop, recommended dose of nitrogen (150 kg N/ha), phosphorus (60 kg P_2O_5/ha) and potash (60 kg K_2O/ha were applied. The fertilizers were schedule as, 1/3rd dose of nitrogen and full dose of phosphorus and potash as basal, remaining 2/3rd nitrogen was applied as top dressing in two splits after 1st at knee height stage and 2nd at initiation of tasseling stage in both the seasons. In wheat crop, recommended dose of nitrogen (150 kg/ ha), phosphorus (60 kg P/ha), potash (40 kg K/ha) and zinc sulphate 21% (25 kg/ha) were applied as per the schedule of: 1/3rd dose of nitrogen and full dose of phosphorus, potash and zinc at sowing time, remaining 2/3rd nitrogen was applied as top dressing in two splits after 1st and 2nd irrigation in both the seasons. The maize crop was harvested manually on 6th October and 8th October, during *Kharif* 2020 and 2021, respectively. The wheat crop was harvested on 19th and 15th April, during *Rabi* 2020-21 and 2021-22, respectively.

Observation recorded and data analysis

Weeds samples were taken from two randomly selected spots in each plot at 20, 40 and 60 DAS and

Table 1. Detail of the treatments

Planting methods	
M_1	Zero-tillage sowing with press wheel (with paddy residues 6 t/ha) *fb* zero till wheat (ZTW)
M_2	Zero-tillage sowing with press wheel (without residues) *fb* ZTW
M_3	Ridge sowing with dibbling method (with paddy residues 6 t/ha) *fb* conventional till wheat (CTW)
M_4	Ridge sowing with dibbling method (without residues) *fb* CTW
M_5	Multi crop ridge planter (with paddy residues 6 t/ha) *fb* CTW
M_6	Multi crop ridge planter (without residues) *fb* CTW
M_7	Raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds)
M_8	Raised bed wide bed planter (without residues) *f* ZTW (reshaping of beds)
M_9	Pneumatic maize planter (with paddy residues 6 t/ha) *fb* ZTW
M_{10}	Pneumatic maize planter (without residues) *fb* ZTW

in wheat crop at 30, 60 and 90 DAS using quadrat measuring 0.5 m x 0.5 m. The grassy weeds, broad-leaved weeds and sedges were collected separately. The samples were oven dried at 70^{0}C till constant weight was achieved. Then dried weed samples weighed and the dry weight was expressed as weed biomass (g/m^2) before subjecting to statistical analysis. Grain yield of maize was recorded after harvesting of cobs at physiological maturity from net plot area (4 middle rows leaving 2.0 m on each side). The harvested cobs were air dried, shelled and grains were cleaned and weighed from each plot. Grain yield/ha was computed and expressed in t/ha. Grains of wheat crop were separated with the help of plot thresher and yield was recorded from each net plot area. The grain yield thus obtained from net plot area was converted into t/ha. Data collected during the study were statistically analysed by using the technique of analysis of variance.

RESULTS AND DISCUSSION

Weed infested

In *Kharif* season, observed major broad-leaved weeds were: *Trianthema portulacastrum, Phyllanthus niruri, Commelina benghalensis, Amaranthus viridis, Convolvulus arvensis.* and *Euphorbia hirta*. Among grassy weeds, *Cynodon dactylon, Dactyloctenium aegyptium, Leptocloa chinesis, Digitaria sanguinalis, Sorghum halepense and Echinochloa crus-galli* were dominant. Among sedges, *Cyperus rotandus* was the major weed infesting in field. In *Rabi* season, broad-leaved weeds observed were: *Rumex dentatus, Medicago denticulata*, *Coronopus didymus*, *Anagallis arvensis, Cirsium arvense, Convolvulus arvensis, Fumaria parviflora*, *Malva parviflora*, while, grassy weeds were: *Phalaris minor* and *Avena ludoviciana*.

Weed density and biomass in maize

In present study, weed density and biomass was significantly affected by different planting methods and weed management treatments. Among planting methods, raised bed wide bed planter with paddy residues 6 t/ha *fb* zero till wheat (ZTW) reshaping of beds resulted in significantly lower density compared to rest of the treatments, but statistically at par with zero-tillage sowing with press wheel (with paddy residues 6 t/ha) *fb* ZTW at 20 and 60 DAS during both years (**Table 2**). At 60 DAS, raised bed wide bed planter with paddy residues 6 t/ha *fb* ZTW reshaping of beds reduced grassy, broad- leaved and sedges density by 94.5-94.9%, 70.6-72.4% and 89.5-91.4%, respectively during the study years as compared to sowing of maize with pneumatic planter without residues *fb* ZTW, having maximum density of all

Table 2. Effect of different planting methods and weed management treatments on weed density (no. /m^2) at 20 and 60 DAS in maize 2021 and 2022

Treatment	2021						2022					
	20 DAS			60 DAS			20 DAS			60 DAS		
	Broad-leaved	Grasses	Sedges	Broad-leaved	Grasses	Sedges	Broad-leaved	Grasses	Sedges	Broad-leaved	Grasses	Sedges
Planting methods												
M_1	2.3(3.6)	2.2 (2.2)	2.8 (4.7)	3.3 (7.5)	3.0 (6.0)	3.8 (12.5)	2.7 (4.2)	2.6 (3.5)	3.1 (6.0)	3.5 (9.2)	3.2 (7.2)	4.0 (14.5)
M_2	3.4 (8.1)	5.0 (22.5)	4.1 (13.0)	3.7 (12.0)	5.7 (34.8)	5.3 (31.7)	3.6 (9.2)	5.3 (25.7)	4.5 (6.1)	4.0 (13.8)	5.9 (37.2)	5.4 (33.5)
M_3	3.2 (6.7)	2.9 (4.8)	3.6 (9.2)	3.5 (9.3)	3.6 (10.7)	4.9 (24.2)	3.5 (8.2)	3.3 (6.5)	3.8 (10.3)	3.8 (11.0)	3.8 (12.3)	5.1 (26.2)
M_4	4.5 (16.2)	5.8(31.0)	5.4 (25.5)	4.3 (17.3)	7.0 (53.8)	6.3 (44.2)	4.6 (17.8)	6.1 (35.3)	5.7 (29.3)	4.5 (19.2)	7.3 (56.8)	6.5 (47.0)
M_5	3.5 (8.3)	3.3 (7.0)	4.0 (11.8)	4.1 (13.7)	3.9 (12.7)	5.0 (26.2)	3.7 (9.8)	3.5 (8.5)	4.1 (13.3)	4.3 (15.3)	4.2 (14.8)	5.3 (28.5)
M_6	4.9 (20.3)	6.2 (37.0)	5.7 (29.8)	4.6 (20.5)	7.3 (59.3)	6.6 (51.3)	5.2 (23.3)	6.7 (43.5)	6.1 (34.3)	4.8 (2.3)	7.5 (62.2)	6.8 (53.7)
M_7	2.6 (3.5)	2.0 (1.5)	2.5 (3.0)	3.1 (6.2)	2.6 (3.5)	2.8 (4.8)	2.5 (3.0)	2.2 (1.9)	2.6 (3.7)	3.2 (7.2)	2.8 (4.8)	3.1 (6.3)
M_8	3.2 (6.6)	4.7(18.3)	3.9 (11.2)	3.7 (11.2)	5.4 (31.8)	5.2 (29.3)	3.3 (7.7)	4.8 (20.2)	4.0 (12.0)	3.9 (14.7)	5.6 (34.5)	5.4 (31.8)
M_9	3.6(8.8)	3.5(8.3)	4.1 (13.0)	4.3 (15.3)	4.2 (14.7)	5.3 (19.2)	3.7 (10.0)	3.7 (10.0)	4.2 (14.2)	4.5 (17.0)	4.4 (16.5)	5.5 (31.2)
M_{10}	4.9(20.7)	6.4 (40.0)	4.4(16.6)	7.7 (64.1)	7.0 (56.1)	5.5 (24.2)	6.6 (42.7)	6.1 (34.1)	4.5 (19.0)	7.9 (67.3)	7.2 (60.1)	7.2 (60.1)
LSD (p=0.05)	0.4	0.3	0.4	0.4	0.5	1.0	0.4	0.4	0.5	0.5	0.4	0.97
Weed management												
W_1	1.0 (0.0)	1.0 (0.0)	1.0 (0.00)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
W_2	4.8(16.2)	6.0 (32.0)	5.7 (24.9)	6.7 (34.4)	9.0 (76.4)	10.1(91.0)	5.1 (18.3)	6.3 (35.1)	6.0 (28.3)	7.0 (37.5)	9.3 (80.4)	10.3 (95.3)
W_3	4.3(12.1)	4.8 (18.2)	4.9 (16.7)	3.9 (9.1)	4.9 (18.9)	4.6 (13.7)	4.5(13.8)	5.2 (21.4)	5.2 (19.4)	4.2 (10.9)	5.2 (21.5)	4.9 (16.7)
W_4	4.4(12.9)	4.9 (18.8)	5.2 (20.0)	4.2 (10.6)	5.2 (21.2)	5.2 (19.0)	4.6 (14.8)	5.3 (22.5)	5.4 (21.8)	4.5 (12.7)	5.5 (23.5)	5.4 (21.1)
LSD (p=0.05)	0.45	0.5	0.4	0.6	0.5	0.6	0.5	0.4	0.5	0.7	0.7	0.7

*Original figures in parentheses were subjected to square root transformation ($\sqrt{x+1}$) before statistical analysis.
ZT sowing with press wheel with (M_1) and without (M_2) paddy residues 6 t/ha *fb* ZTW; Ridge sowing with dibbling method with (M_3) and without (M_4) paddy residues 6 t/ha *fb* CTW Multi crop ridge planter with (M_5) and without (M_6) paddy residues 6 t/ha *fb* CTW; Raised bed wide bed planter with (M_7) and without (M_8) paddy residues 6 t/ha) *fb* ZTW (reshaping of beds); Pneumatic maize planter with (M_9) and without (M_{10}) paddy residues 6 t/ha) *fb* ZTW; W_1: Weed free check, W_2: Weedy check, W_3: Tembotrione 120 g/ha at 15 DAS and W_4: Topramezone 25.2 g/ha at 15 DAS

types of weeds. Moreover, maize planting with raised bed wide bed planter with paddy residues 6 t/ha *fb* ZTW reshaping of beds reduced grassy, broad-leaved and sedges biomass by 97.4-97.9%, 86.4-87.2% and 91.2-93.0%, respectively during the study years, as compared to sowing with pneumatic planter without residues *fb* ZTW, having maximum biomass of all types of weeds.

The surface mulching of paddy residue and sowing of maize on raised bed wide bed planter *fb* ZTW reshaping of beds reduced biomass of grassy (93.1-94.5%), broad-leaved (66.0-66.5) and sedges (46.6-86.7%) significantly as compared to without surface mulching for the same planting system. Zero tillage with and without surface mulching resulted in reduced weed biomass as compared to conventional ridge sowing with and without surface mulching with paddy residue. The reduction in biomass of grassy weed due to surface mulching of paddy residue was similar in ZT sowing with press wheel *fb* ZTW (80.7-82.8%) and ridge sowing with dibbling method (78.30-86.1%), while higher for sedges in former planting system (56.7-60 *vs* 44.3-45.3%) (**Table 3**). While, reduction in broad-leaved weeds was more in ridge sowing with dibbling method (42.5-46.2%) as compared to ZT sowing with press wheel (33.7-37.5%). Raised bed planting method resulted in lower weed density which increased water and nutrient use efficiency confirming findings of Fahong *et al.* (2004) and Ali and Seyedeh (2008). Govaerts *et al.* (2005) and Ortega *et al.* (2008) also reported that raised bed sowing method produced higher grain yield of maize and the minimum weeds biomass.

Among weed control treatments, tembotrione 120 g/ha PoE at 15 DAS resulted in significantly lower weed density of grassy, broad- leaved and sedges at 20 and 60 DAS and weed biomass at 60 DAS which was at par with topramezone 25.2 g/ha at 15 DAS, while maximum weed density was recorded in weedy check during both the years (**Table 2** ad **3**). The percentage reduction in weed density at 60 DAS in comparison to weedy check was recorded higher with tembotrione 120 g/ha i.e. grassy (73.3-75.2%), broad-leaved weed (70.8-73.5%) and sedges (82.4-84.9%) as compared to topramezone 25.2 g/ha (70.7-72.3, 66.2-69.2, 77.9-78.8%, respectively). Similarly, percentage reduction in biomass in comparison to weedy check was higher with tembotrione 120 g/ha i.e. grassy (79.3-80.7%), broad-leaved weed (82.4-84.1%) and sedges (82.7-87.8 %) as compared to topramezone 25.2 g/ha (76.6-77.5, 79.4-81.4, 81.3-82.8%, respectively). Better weed control, higher WCE were observed with topramezone + atrazine 25.2 + 250 g/ha followed by

Table 3. Effect of different planting methods and weed management on weeds biomass (g/m^2) of at 60 DAS in maize 2021 and 2022

Treatment	60 DAS (2021)			60 DAS (2022)		
	Broad-leaved	Grasses	Sedges	Broad-leaved	Grasses	Sedges
Planting methods						
M_1	2.6 (4.3)	2.1 (1.8)	1.7 (0.9)	2.8 (5.2)	2.2 (2.2)	1.8 (1.0)
M_2	3.4 (10.1)	4.4 (19.6)	2.2 (2.6)	3.6 (11.5)	4.6 (20.8)	2.3 (2.8)
M_3	3.0 (6.1)	2.6 (4.4)	2.0 (1.6)	3.2 (7.2)	2.8 (5.1)	2.1 (1.8)
M_4	4.1 (16.3)	5.8 (35.1)	2.5 (3.6)	4.3 (17.9)	6.0 (37.0)	2.5 (3.8)
M_5	3.3 (9.0)	2.8 (5.3)	2.1 (1.8)	3.6 (10.0)	3.0 (6.1)	2. 1 (1.9)
M_6	4.5 (20.8)	6.1 (39.3)	2.6 (4.2)	4.7 (22.5)	6.2 (41.1)	2.6 (4.4)
M_7	2.4 (3.1)	1.8 (0.9)	1.5 (0.3)	2.5 (3.6)	1.9 (1.3)	1.6 (0.4)
M_8	3.3 (9.2)	4.2 (16.8)	2.2 (2.4)	3.6 (10.8)	4.3 (18.2)	2.2 (2.6)
M_9	3.7 (12.2)	3.0 (5.9)	2.1 (2.0)	3.9 (13.4)	3.1 (6.7)	2.2 (2.1)
M_{10}	4.9 (24.5)	6.5 (45.4)	2.7 (4.6)	5.1 (26.5)	6.6 (47.6)	2.7 (4. 9)
LSD (p=0.05)	0.3	3.0	0.4	0.3	0.3	0.26
Weed management						
W_1	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.00 (0.0)	1.0 (0.0)	1.0 (0.0)
W_2	6.6 (34.3)	7.2 (49.3)	3.6 (7.4)	6.8 (37.2)	7.3 (51.6)	3.6 (7.7)
W_3	3.2 (5.5)	3.6 (9.5)	1.9 (0.9)	3.4 (6.6)	3.8 (10.7)	2.0 (1.3)
W_4	3.4 (6.4)	3.9 (11.1)	2.1 (1.3)	3.7 (7.7)	4.1 (12.1)	2.2 (1.4)
LSD (p=0.05)	0.5	0.3	0.2	0.6	0.4	0.3

*Original figures in parentheses were subjected to square root transformation ($\sqrt{x+1}$) before statistical analysis.
ZT sowing with press wheel with (M_1) and without (M_2) paddy residues 6 t/ha *fb* ZTW; Ridge sowing with dibbling method with (M_3) and without (M_4) paddy residues 6 t/ha *fb* CTW Multi crop ridge planter with (M_5) and without (M_6) paddy residues 6 t/ha *fb* CTW; Raised bed wide bed planter with (M_7) and without (M_8) paddy residues 6 t/ha) *fb* ZTW (reshaping of beds); Pneumatic maize planter with (M_9) and without (M_{10}) paddy residues 6 t/ha) *fb* ZTW; W_1: Weed free check, W_2: Weedy check, W_3: Tembotrione 120 g/ha at 15 DAS and W_4: Topramezone 25.2 g/ha at 15 DAS

tembotrione + atrazine 105 + 250 g/ha as observed by Jonathon *et al.* (2013) which might be due to higher efficacy of herbicides against complex weed flora.

Weed density and biomass in wheat

Raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds) resulted in maximum percentage reduction in density of grassy (69-72.3%) and broad-leaved weeds (71.5-75.3%) and biomass (72.5-75.6% of grassy weeds and 74.2-75.3% of broad-leaved weeds) as compared to sowing of maize with multi crop ridge planter (without residues) *fb* CTW, which resulted in maximum infestation of grassy and broad-leaved weeds at 60 DAS. Weed control treatment failed to affect significantly the weed density and biomass of broad-leaved and grassy weeds at 60 DAS during both the years (**Table 4**). Ghosh *et al.* (2021) also reported lesser weed infestation under conservation-based tillage system *i.e.* permanent beds (34%) and permanent narrow beds (28%) than the conventional tillage (CT) practice due to higher emergence of weeds in later one. Higher infestation of weeds in CT might be due to soil inversion caused by tillage, greater aeration and periodical irrigation application (Baghel *et al.* 2020). CA practices helped in preventing proliferation of weeds and minimized negative impact of weeds on crop productivity. Crop residue retention with zero tillage (ZT) could delay as well as suppress weed germination and emergence. It could be a multi-tactic approach for sustainable weed management in crop rotations, reducing the need for herbicides usage (Christoffoleti *et al.* 2007, Susha *et al.* 2014, Nath *et al.* 2016).

Maize and wheat grain yield

The grain yield is the principal criterion for evaluating efficiency of various treatments because ultimate effects of experimental variables are reflected in the form of final grain yield. It is a function of effective tillers, number of grains per spike and test weight. The maximum maize grain, stover and biological yield was obtained with raised bed wide bed planter (with rice residues 6 t/ha) *fb* ZTW (reshaping of beds) which was significantly higher than all the planting methods but at par with zero-tillage sowing with press wheel (with rice residues 6 t/ha) *fb* ZTW during both the years (**Table 5**). Narang *et al.* (2015) observed maximum grain yield with raised bed maize planter, multi-crop planter and manually operated planter

Grain yield of maize was significantly higher in weed free check as compared to weedy check, but at

Table 4. Effect of different planting methods, weed management on weeds density (no./m^2) and biomass (g/m^2) at 60 DAS in wheat 2020-21, 2021-22

Treatment	60 DAS (2020-21)				60 DAS (2021-22)			
	Broad-leaved		Grasses		Broad-leaved		Grasses	
	(No./m^2)	(g/m^2)	(No./m^2)	(g/m^2)	(No./m^2)	(g/m^2)	(No./m^2)	(g/m^2)
Planting methods								
M_1	4.8 (19.2)	4.0 (11.9)	3.1 (6.2)	2.6 (3.7)	4.9 (20.7)	4.1 (12.8)	3.4 (7.7)	3.4 (4.5)
M_2	5.2 (24.0)	4.2 (13.5)	3.3 (7.4)	2.9 (4.97)	5.1 (25.1)	4.3(14.4)	3.6 (8.9)	3.7 (5.8)
M_3	6.0 (33.0)	5.8 (31.0)	4.1 (13.3)	3.6 (9.4)	7.1 (49.6)	6.0 (33.0)	4.5 (16.3)	4.7 (11.2)
M_4	6.1 (34.9)	6.0 (32.9	4.4 (15.4)	3.9 (11.1)	7.25 (52.3)	6.1 (34.9)	4.7 (18.4)	5.0 (12.9)
M_5	6.1 (34.3)	5.8 (31.2)	4.3 (14.8)	3.8 10.2)	7.1 (49.8)	6.0 (33.2)	4.6 (17.8)	4.8 (12.0)
M_6	6.4 (38.8)	6.1 (34.2)	4.6 (17.4)	4.0 (11.7)	7.4 (54.3)	6.2 (36.2)	4.9 (20.4)	5.1 (13.5)
M_7	3.6 (9.6)	3.5 (8.4)	2.9 (4.8)	2.4 (2.9)	4.4 (15.5)	3.6 (9.4)	3.2 (6.3)	3.2 (3.7)
M_8	4.2 (13.9)	3.7 (9.6)	3.0 (5.4)	2.7 (4.1)	4.6 (17.4)	3.8 (10.5)	3.3 (6.9)	3.5 (4.9)
M_9	5.3 (24.7)	4.3 (15.0)	3.40 (7.8)	2.8 (4.5)	5.4 (25.8)	4.4 (16.0)	3.6 (9.3)	3.6 (5.4)
M_{10}	5.6 (27.8)	4.6(17.6)	3.6 (9.0)	3.1 (5.8)	5.7 (29.9)	4.7 (18.6)	3.8 (10.5)	3.9 (6.7)
LSD (p=0.05)	0.16	0.2	0.15	0.1	0.2	0.2	0.1	0.1
Weed management								
W_1	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
W_2	6.9 (36.6)	6.1 (28.3)	4.7 (14.4)	4.0 (9.9)	7.6 (46.7)	6.3 (30.1)	5.0 (17.2)	5.3 (11.6)
W_3	6.70 (34.2)	6.0 (26.3)	4.4 (12.6)	3.8 (8.4)	7.4 (43.7)	6.1 (28.1)	4.8 (15.4)	5.0 (10.1)
W_4	6.67 (33.6)	6.1 (27.6)	4.6 (13.6)	3.9 (9.0)	7.5 (45.1)	6.3 (29.5)	4.9 (16.4)	5.1 (10.6)
LSD (p=0.05)	0.6	0.5	0.6	0.5	0.6	0.5	0.5	0.6

*Original figures in parentheses were subjected to square root transformation ($\sqrt{x+1}$) before statistical analysis.
ZT sowing with press wheel with (M_1) and without (M_2) paddy residues 6 t/ha *fb* ZTW; Ridge sowing with dibbling method with (M_3) and without (M_4) paddy residues 6 t/ha *fb* CTW Multi crop ridge planter with (M_5) and without (M_6) paddy residues 6 t/ha *fb* CTW; Raised bed wide bed planter with (M_7) and without (M_8) paddy residues 6 t/ha) *fb* ZTW (reshaping of beds); Pneumatic maize planter with (M_9) and without (M_{10}) paddy residues 6 t/ha) *fb* ZTW; W_1: Weed free check, W_2: Weedy check, W_3: Tembotrione 120 g/ha at 15 DAS and W_4: Topramezone 25.2 g/ha at 15 DAS

par with tembotrione 120 g /ha at 15 DAS and topramezone 25.2 g /ha at 15 DAS during both the years. The interaction among planting methods and weed management was significant (**Table 6**). The maximum grain yield was found with planting method raised bed wide bed planter (with rice straw 6 t/ha) *fb* ZTW (reshaping of beds) with combination tembotrione 120 g/ha at 15 DAS, topramezone 25.2 g /ha at 15 DAS and weed free check followed by zero-tillage sowing with press wheel (with rice straw 6 t/ ha) *fb* ZTW with combination tembotrione 120 g/ha, topramezone 25.2 g /ha at 15 DAS and weed free check; and raised bed wide bed planter (without residues) *fb* ZTW (reshaping of beds) with combination tembotrione 120 g/ha at 15 DAS and topramezone 25.2 g /ha at 15 DAS. Higher yield and yield attributes raised bed wide bed planter with rice residues 6 t/ha *fb* ZTW reshaping of beds were due to significant reduction in weed density and biomass of grassy (94.5-94.9 and 97.4-97.9%), broad-leaved weeds (70.6-72.4 and 86.4-87.2%) and sedges (89.5-91.4 and 91.2-93.0%), respectively at stages of observations during both the study years, as compared to sowing of maize with pneumatic planter without residues *fb* ZTW, having maximum density and dry weight of all types of weeds. Kumar *et al.* (2018) also reported higher grain yield under bed planting over tillage practices along with zero tillage practices, while lowest grain yield was recorded under conventional tillage practice. Jat *et al.* (2013) also found significant effect of tillage practices on maize yield as higher grain yield was recorded under permanent bed compared to conventional tillage flat, which was statistically at par with zero tillage. Lower yield under CT was due to heavy rains that caused temporary flooding and adversely affected crop growth. Maize is known to be quite sensitive to excess water stress and yields poorly under water logged conditions (Dhillon *et al.* 1998, Lal *et al.* 1988). Kaur and Chhina (2019) studied that maximum plant height, leaf area index, dry matter accumulation, number of cobs/plant, number of grains/cob and grain yield was significantly higher in double row bed planting as compared to conventional tillage in spring maize.

The grain and straw yield of wheat increased irrespective of different planting methods. Among planting methods raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds) produced maximum grain yield as compared to all planting methods but statistically at par with raised bed wide bed planter (without residues) *fb* ZTW (reshaping of beds) and zero-tillage sowing with press wheel (with paddy residues 6 t/ha) *fb* ZTW, respectively during both the years (**Table 5**). Chandra

Table 5. Effect of tested planting methods and weed management treatments on yield and economics of maize- wheat cropping system during 2020-21 and 2021-22

Treatment	Maize grain yield (t/ha)		Wheat grain yield (t/ha)		Maize equivalent yield (t/ha)		Net returns (₹/ha)		B:C	
	2020	2021	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
Planting methods										
M_1	9.03	9.26	5.74	5.97	14.94	15.25	149813	171769	1.73	1.84
M_2	7.28	7.44	5.59	5.82	13.03	13.30	110924	129991	1.55	1.65
M_3	8.04	8.25	5.43	5.62	13.63	13.90	98314	118088	1.42	1.52
M_4	6.45	6.67	5.30	5.58	11.91	12.29	63440	83287	1.28	1.37
M_5	7.62	7.90	5.29	5.46	13.07	13.39	92934	113333	1.42	1.51
M_6	5.64	5.87	5.23	5.57	11.03	11.48	49312	69976	1.23	1.32
M_7	9.43	9.66	6.16	6.21	15.78	15.92	157128	184941	1.73	1.88
M_8	7.64	7.89	5.96	6.10	13.57	14.03	112318	144752	1.53	1.71
M_9	7.83	7.96	5.63	5.90	13.63	13.90	111990	132318	1.52	1.62
M_{10}	6.11	6.25	5.45	5.77	11.72	12.06	72501	92561	1.34	1.44
LSD (p=0.05)	0.43	0.42	0.23	0.25	0.51	0.35	-	-	-	-
Weed management										
W_1	8.13	8.36	5.63	5.87	13.93	14.27	113026	136492	1.52	1.63
W_2	5.79	5.91	5.45	5.70	11.40	11.65	63065	81803	1.30	1.40
W_3	8.06	8.31	5.61	5.83	13.84	14.17	116382	139719	1.55	1.66
W_4	8.05	8.27	5.54	5799	13.76	14.11	114997	138392	1.54	1.65
LSD (p=0.05)	0.51	0.52	NS	N.S	0.85	0.62	-	-	-	-

*Original figures in parentheses were subjected to square root transformation ($\sqrt{x+1}$) before statistical analysis.
ZT sowing with press wheel with (M_1) and without (M_2) paddy residues 6 t/ha *fb* ZTW; Ridge sowing with dibbling method with (M_3) and without (M_4) paddy residues 6 t/ha *fb* CTW Multi crop ridge planter with (M_5) and without (M_6) paddy residues 6 t/ha *fb* CTW; Raised bed wide bed planter with (M_7) and without (M_8) paddy residues 6 t/ha) *fb* ZTW (reshaping of beds); Pneumatic maize planter with (M_9) and without (M_{10}) paddy residues 6 t/ha) *fb* ZTW; W_1: Weed free check, W_2: Weedy check, W_3: Tembotrione 120 g/ha at 15 DAS and W_4: Topramezone 25.2 g/ha at 15 DAS

and Kumar (2019) also reported that bed planting system had its own advantage in comparison to the flat planting methods. Majeed *et al.* (2015) observed that wheat crop sown on beds produced higher grain yield and nutrient use efficiency relative to the conventional flat method. Additionally, bed planting system facilitates mechanical cultivation as an alternative method of weed control during the crop growing season and saving of irrigation water than conventional flood irrigation. Similarly, among all the planting methods the maize equivalent yield was significantly higher with raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds) (15.78 and 15.92 t/ha) as compared to rest of the planting methods in maize-wheat cropping system.

Weed management treatment did not influence grain yield, stover yield and biological yield and grain yield was not significantly different amongst treatments. Maximum grain yield was observed in weed free check and lower grain yield was observed in weedy check during both the of years study (**Table 5**). Among weed management treatments, maize equivalent yield was significantly higher with weed free check as compared to weedy check, but was statistically at par with tembotrione 120 g/ha and topramezone 25.2 g/ha at 15 DAS during both the study years (**Table 5**). Das *et al.* (2018) also reported higher maize equivalent yield with permanent broad and narrow bed with residue followed by zero tillage with and without residue than conventional tillage (farmers' practice).

Economics

The economics of various treatments were calculated by taking into account the current rates of inputs, labor, other expenses, and market values of the output, specifically the grain and straw yield under various treatments (**Table 5**). Zero-tillage sowing with press wheel (without residues) *fb* ZTW had the lowest cost of cultivation, while multi-crop ridge planter (with paddy residues 6 t/ha) *fb* CTW had the highest cost of cultivation in both years. Raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds) had the highest gross returns, net returns, and B C ratio (1.73 and 1.88, respectively) confirming Kumar *et al.* (2018). This was due to lower labour cost and mechanization, lower fertilizer application. Ahmed *et al.* (2018) opined that maize-wheat cropping system could maintain system productivity and reduce tillage cost, that would help farmers to increase profits. Further, farmers of maize-wheat system could improve productivity through adoption of mechanized bed planting for maize and mechanized wheat planting with zero till drill under tilled and no till conditions. Amongst weed management treatments, tembotrione 120 g/ha PoE at 15 DAS recorded the highest gross returns, net returns and highest B-C ratio due to the lowest cost of cultivation during both years of study (**Table 5**).

Conclusion

Raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds) recorded

Table 6. Interaction effect of planting methods and weed management on grain yield of maize

Treatment	Weed management Grain yield (t/ha)							
	2020				2021			
	Weed free	Weedy check	Tembo-trione 120 g/ha	Toprame-zone 25.2 g/ha	Weed free	Weedy check	Tembotrione 120 g/ha	Toprame-zone 25.2 g/ha
Planting methods								
Zero-tillage sowing with press wheel (with paddy residues 6 t/ha) *fb* ZTW	9.14	9.01	9.07	9.09	9.32	9.09	9.27	9.20
Zero-tillage sowing with press wheel (without residues) *fb* ZTW	8.15	6.74	8.11	8.08	8.50	6.95	8.41	8.34
Ridge sowing with dibbling method (with paddy residues 6 t/ha) *fb* CTW)	8.29	8.16	8.25	8.24	8.35	8.17	8.31	8.29
Ridge sowing with dibbling method (without residues) *fb* CTW	7.86	2.82	7.73	7.68	7.96	2.43	7.83	7.76
Multi crop ridge planter (with paddy residues 6 t/ha) *fb* CTW	7.87	7.63	7.76	7.72	8.00	7.72	7.92	7.83
Multi crop ridge planter (without residues) *fb* CTW	7.05	2.45	7.00	6.940	7.47	2.12	7.22	7.17
Raised bed wide bed planter (with paddy residues 6 t/ha) *fb* ZTW (reshaping of beds)	9.50	9.21	9.46	9.28	9.77	9.39	9.61	9.40
Raised bed wide bed planter (without residues) *fb* ZTW (reshaping of beds)	9.05	6.20	9.01	8.93	9.20	6.67	9.14	9.03
Pneumatic maize planter (with paddy residues 6 t/ha) *fb* ZTW	8.18	7.96	8.16	8.08	8.54	8.30	8.54	8.46
Pneumatic maize planter (without residues) *fb* ZTW	7.54	2.32	7.48	7.30	7.68	2.22	7.56	7.52
Factor (B) at same level of A								
LSD (p=0.05)			1.03				0.97	
Factor (A) at same level of B								
LSD (p=0.05)			1.11				0.98	

lower weed density and biomass of all types of weeds; higher maize and wheat grain, stover and biological yield than multi crop ridge planter (without residues) *fb* CTW during both the years. Among weed management treatments, maize equivalent yield was significantly higher with weed free check which was statistically at par with tembotrione 120 g/ha and topramezone 25.2 g/ha at 15 DAS. However, tembotrione 120 g/ha PoE at 15 DAS recorded the highest B-C ratio due to the lowest cost of cultivation during both years of study.

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RESEARCH ARTICLE

Weed dynamics and growth of soybean in response to different sowing dates and weed management treatments under rainfed conditions of Nagaland

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ABSTRACT

An experiment was conducted at the School of Agricultural Sciences, Medziphema Campus, Nagaland University, Nagaland, India, during the *Kharif* seasons of 2021 and 2022. The objective was to examine the weed dynamics and the growth of soybean (*Glycine max* (L.) Merill) in response to different sowing dates and weed management treatments. A split-plot design was employed, with three sowing dates in the main plots and seven integrated weed management treatments in the sub-plots. The pooled results over the two years indicated that soybean sown on June 15 exhibited significantly lower total weed density and biomass and higher weed control efficiency. The June 15 sowing date also resulted in maximum soybean plant height, branches per plant, dry matter production, leaf area index, number of nodules, dry weight of nodules, seed yield and stover yield. Among the herbicide treatments, the sequential treatment of pre-emergence application (PE) pendimethalin 1000 g/ha followed by (*fb*) post-emergence application (PoE) of imazethapyr 100 g/ha at 20 days after sowing (DAS) recorded lower weed density, weed biomass, higher weed control efficiency with enhanced growth attributes and yield of soybean. It was concluded that early sowing (on June 15) and application of pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS, resulted in significant control of weeds and increased growth and yield of soybean.

Keywords: Soybean, Soil Solarization, Mulching, Pendimethalin, Imazethapyr, Weed management

INTRODUCTION

Soybean [*Glycine max* (L.) Merill] is a significant crop grown worldwide. It is used for food like tofu, soy milk, animal feed, products like biofuel and soy oil. Soybeans have the highest protein content among oilseeds, with 40-45% protein and 20-23% oil. They also have nutrients like calcium, phosphorus, iron, and vitamins. Soybeans provide complete protein with eight essential amino acids (Berad *et al*. 2016) and enriches soil through nitrogen fixation (Devi *et al*. 2011). India is the fifth largest producer after Brazil, USA, Argentina, China. In India soybean is mainly grown in Madhya Pradesh, Maharashtra, Rajasthan, and Karnataka (SOPA 2023). Despite production challenges, soybean remains vital to India agricultural sector due to health awareness and export opportunities.

Soybean productivity is significantly affected by management strategies, environmental conditions, and cultivar genetics (Nleya *et al*. 2020). The timing of sowing is crucial as it determines the environmental conditions such as temperature, photoperiod, and moisture that the crop will encounter during critical growth stages. Early sowing facilitates optimal utilization of the growing season and solar radiation, often resulting in extended vegetative periods and increased yields (Guo *et al*. 2022). Empirical studies indicated that early sowing enhances plant height, pod numbers, growth rates, and seed yield (Kaleri *et al*. 2023). The earlier sowing of soybeans enhanced growth and increased seed yield by 59.95% compared to later sowing dates (Jagtap *et al*. 2019). Furthermore, the sowing date significantly influences weed population, nutrient uptake, and overall productivity.

Among the constraints affecting soybean productivity in India, weed infestation is particularly severe. Soybean crop is subjected to continuous infestation of grassy, broad-leaved, and sedge weeds, resulting in growth and yield reductions ranging from 58% to 85%, with the extent of impact contingent upon the type and intensity of the weed presence (Padre *et al*. 2022). Additionally, weed pressure contributes to reduced nodulation and nitrogen fixation and elevates the risk of diseases and pests

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(Norsworthy *et al.* 2012). The critical period for crop and weed competition in soybean cultivation extends for 30 to 40 days post-sowing. Previous studies have demonstrated that superior weed control efficiency, along with enhanced soybean growth attributes and seed yield, can be achieved through hand hoeing twice (Rupareliya *et al.* 2020). However, hand weeding is laborious and is becoming costly due to increased labour shortage and labour wages. Thus, herbicide application offers significant advantages, including high efficiency in weed control, high selectivity, and cost-effectiveness compared to alternative weed management strategies (El-Metwally *et al.* 2017, Verma and Kushwaha 2019). Thus, the present study was conducted to identify suitable weed control measures in soybean sown under different sowing dates under rainfed conditions of Nagaland.

MATERIALS AND METHODS

Two-year field experiments were conducted during the *Kharif* seasons of 2021 and 2022 at the Agronomy Research Farm, School of Agricultural Sciences, Nagaland University, Medziphema Campus. The soil of the experimental site is sandy loam soil, acidic in reaction (pH 4.74), with medium organic carbon content (1.50%), available nitrogen (416.24 kg/ha), available phosphorus (18.60 kg/ha), and high available potassium (218.70 kg/ha). A split-plot design with three replications was used. Sowing dates were assigned to the main plots, *viz.* June 15, June 30, and July 15. Weed control treatments were allocated to sub-plots, *viz.* soil solarization with black polythene 25 days before sowing followed by (*fb*) hand weeding at 30 days after sowing (DAS), mulching with paddy straw at 5 t/ha *fb* hand weeding at 30 DAS, pre-emergence application (PE) of pendimethalin 1000 g/ha *fb* post-emergence application (PoE) of imazethapyr 100 g/ha at 20 DAS, pendimethalin 1000 g/ha *fb* intercultural operations at 30 DAS, imazethapyr 100 g/ha at 20 DAS *fb* intercultural operations at 30 DAS, hand weeding twice at 20 and 40 DAS, and weedy check, control. The plot size was 4 m × 3 m (12 m²) with plant spacing of 30 cm between rows and 10 cm between plants, using a seed rate of 70 kg/ha. Prior to final land preparation, well-decomposed farmyard manure (FYM) was uniformly applied at 10 t/ha and thoroughly incorporated into the soil. Soybean seeds (JS 97-52) were soaked overnight and inoculated with *Bradyrhizobium japonicum* strain before sowing. Seeds were manually sown at a depth of 5 cm. The recommended doses of N, P, and K at 20, 60, and 50 kg/ha, respectively, were applied as a basal dose during final land preparation. Herbicides were applied according to the treatments using a knapsack sprayer at a spray volume of 500 L/ha for both pre- and post-emergence applications. Plant protection measures were implemented to prevent pest attacks. Variables observed included weed species, weed density, weed dry weight (weed biomass), and weed control percentage, were assessed in each plot using a 1 m² quadrat. Data were transformed using the formula "x + 0.5, where x represents the actual weed density and biomass. Standard methods were employed to evaluate plant growth and yields. A combined analysis of variance (one-way ANOVA) over two years was conducted to determine treatment effects. The standard error of means (SEm+) and least significant difference [LSD (p=0.05)] were calculated for each parameter. All data analyses adhered to the principles of split-plot design as described by Gomez and Gomez (1984).

RESULT AND DISCUSSION

Weed flora

The predominant weed species associated with soybean during both years included *Digitaria sanguinalis*, *Eleusine indica*, and *Cynodon dactylon* among the grasses. The identified sedge species were *Cyperus iria* and *Cyperus rotundus*, while the broad-leaved weeds comprised of *Borreria latifolia*, *Ageratum conyzoides*, *Mollugo pentaphylla*, *Alternanthera sessilis*, *Mimosa pudica*, *Amaranthus viridis*, *Cleome rutidosperma*, *Scoparia dulcis*, and *Commelina benghalensis*. Among these, *Digitaria sanguinalis* and *Eleusine indica* predominant and posed greater competitiveness with the soybean (Walling *et al.* 2012, Apon and Nongmaithem 2022).

Effect on weed density and biomass

Variation in weed density was found to be significant with different soybean sowing dates (**Table 1**). At 40- and 60-days post-planting, soybeans sown on June 15 exhibited a reduced weed density compared to those planted at June 30 by 16, 11% and July 15 by 38, 29%, respectively which may be attributed to the early planting's utilization of monsoonal moisture. Early planting facilitated enhanced soybean growth and competitive ability against weeds resulting in lower weed density and lesser availability and usage by weeds of moisture, nutrients, light, and space (Sahu *et al.* 2019).

The application of herbicides, whether pre-emergence or post-emergence, significantly reduced the overall weed occurrence across all species during crop growth compared to the untreated control

(**Table 1**). Throughout all growth stages, the highest total weed density was recorded in the untreated control. The pendimethalin 1000 g/ha *fb* imazethapyr 100 g/ha at 20 DAS, resulted in a substantial reduction in density of grassy, sedge, and broad-leaved weeds at 40 DAS due to the efficacy of both pre- and post-emergence herbicides application. Specifically, pendimethalin, has been identified as the most effective in controlling weeds by inhibiting seed germination and seedling development, particularly during the early stages of crop growth (Zain *et al*. 2020, Hasanuddin *et al*. 2022) and imazethapyr inhibited acetolactate synthase (ALS), a crucial enzyme, thereby impeding weed growth by disrupting cell division, nutrient translocation, hormonal balance, and DNA and cell growth, leading to rapid weed mortality (Emmiganur and Hosmath 2020, Roy *et al*. 2023). Hand weeding twice at 20 and 40 DAS effectively reduced both inter- and intra-row weeds.

The weed biomass increased over time. Among the various sowing dates, soybeans planted on June 15th resulted in a reduction in total weed biomass by 17, 11% and 45, 31% compared to those sown on June 30th and July 15th, respectively. This reduction in weed biomass can be attributed to the lower density of grasses, sedges, and broad-leaved weeds, which led to decreased utilization limited resources, thereby resulting in a lower weeds biomass (Sai *et al*. 2019, Hamoda *et al*. 2021).

The weed biomass increased with higher weed density, as well as with the variation in weed species and their growth. The application of herbicides resulted in a reduction in total weed biomass, as evidenced by their higher weed control efficiency. The highest weed biomass was observed under the weedy check at 40 and 60 DAS (**Table 2**). The pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS resulted in the lowest total weed biomass at 40 DAS. Similarly, at 60 DAS, hand weeding twice at 20 and 40 DAS, recorded the lowest total weed biomass among the herbicidal treatments confirming the findings of Kutariye *et al.* 2021 and Meena *et al.* 2022.

Table 1. Effect of sowing dates and integrated weed management treatments on weed density (no./m^{-2}) at 40,60 DAS (pooled data of 2021-2022)

Treatment	Weed density (no./m^2)							
	Grasses		Sedges		Broad-leaved		Total	
	40 DAS	60 DAS	40 DAS	60 DAS	40 DAS	60 DAS	40 DAS	60 DAS
Sowing dates (P)								
15th June	4.40 (21.6)	5.64 (34.2)	1.79 (3.1)	2.17 (5.1)	4.58 (23.1)	5.72 (35.2)	6.52 (47.9)	8.27 (74.59)
30th June	5.23 (29.6)	6.35 (42.6)	2.08 (4.2)	2.29 (5.7)	5.18 (29.0)	6.29 (41.9)	7.59 (62.9)	9.19 (90.38)
15th July	6.27 (41.2)	7.48 (58.1)	2.52 (6.2)	2.88 (8.7)	6.02 (38.4)	7.18 (53.6)	9.00 (85.9)	10.72 (120.5)
LSD (p=0.05)	0.25	0.18	0.10	0.06	0.09	0.10	0.20	0.09
Weed Management (W)								
Soil solarization 25 DBS *fb* hand weeding at 30 DAS	5.01 (25.4)	6.55 (43.3)	1.95 (3.4)	2.59 (6.3)	5.00 (24.9)	6.85 (46.8)	7.28 (53.8)	9.78 (96.49)
Mulching with paddy straw 5 t/ha *fb* hand weeding at 30 DAS	5.20 (27.2)	6.77 (46.0)	1.98 (3.5)	2.62 (6.5)	5.32 (28.2)	7.32 (53.5)	7.63 (59.0)	10.26 (106.0)
Pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS	3.82 (14.8)	5.22 (27.3)	1.55 (2.0)	2.09 (4.0)	3.42 (11.6)	4.91 (24.0)	5.27 (28.5)	7.40 (55.4)
Pendimethalin 1000 g/ha *fb* intercultural at 30 DAS	4.44 (20.10)	6.12 (37.7)	1.88 (3.1)	2.34 (5.0)	4.51 (20.2)	6.05 (36.6)	6.53 (43.4)	8.87 (79.4)
Imazethapyr 100 g/ha 20 DAS *fb* Intercultural at 30 DAS	4.10 (17.0)	5.86 (34.6)	1.62 (2.2)	2.17 (4.3)	3.84 (14.6)	5.46 (29.8)	5.76 (33.9)	8.25 (68.8)
Hand weeding twice at 20 and 40 DAS	5.81 (33.8)	4.73 (22.3)	2.43 (5.4)	0.90 (0.4)	6.07 (36.8)	4.44 (19.6)	8.69 (76.1)	6.48 (42.4)
Weedy check (control).	8.74 (77.0)	10.16 (103.5)	3.51 (11.9)	4.4 (19.0)	8.67 (75.1)	9.74 (94.7)	12.77 (164)	14.72 (217.4)
LSD (p=0.05)	0.29	0.25	0.11	0.17	0.14	0.20	0.23	0.27

Original values were subjected to square root transformation. Figures in parentheses are the original values. DAS = date of sowing; DBS = days before seeding, fb = followed by; PE = pre-emergence application; PoE = post emergence application

Weed control efficiency (WCE)

Weed control efficiency denotes the relative efficiency of weed control practices compared to weedy check. The higher WCE of 71.42 and 61.65 % at 40 and 60 DAS respectively, were observed when the crop was sown on June 15th. In contrast, the lowest efficiencies were noted with the late sowing date. Samant and Mohanty (2017) also reported the improved weed control efficiency with earlier sowing dates.

The maximum WCE of 87 and 76 % at 40 and 60 DAS respectively, was recorded with pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS, among herbicides treatments, which can be attributed to the minimal weed density, biomass and increased seed yield, respectively, achieved through effective suppression of weed growth (Raj *et al.* 2020, Pawar *et al.* 2022).

Effect on soybean growth and yield

The timing of sowing had a significant influence on the growth of soybeans across all developmental stages (**Table 3**). Due to their photosensitivity, soybeans sown early, on June 15th, exhibited the highest pooled values for plant height, branches/ plant, dry weight/plant, leaf area, root nodules/plant, dry weight of root nodules, seed yield and stover yield in compared to other sowing dates. This may be attributed to early sowing providing soybean plants with favourable climatic conditions and temperatures, as well as a comparatively extended growth period, thereby enabling the plants to optimize their growth and development potential, ultimately resulting in higher yield (Dandge *et al.* 2020). Furthermore, the observed reduction in growth attributes and yield with delayed planting may be due to rapid changes in photoperiod, which expedite the transition to reproductive stages, consequently reducing the time available for vegetative growth (Kumagai and Takahashi 2020).

The pooled mean values over the two years indicate that pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS resulted in significantly enhanced soybean growth parameters (**Table 3**) and the lowest values for these growth attributes and yield were observed in the weedy check plots. The substantial enhancement in growth attributes and yield can be ascribed to the effective management of weeds during critical stages of crop development. This management facilitated improved

Table 2. Effect of sowing dates and integrated weed management treatments on weed biomass (g/m²) at 40,60 DAS (pooled data of 2021-2022)

Treatment	Weed biomass (g/m²)							
	Grasses		Sedges		Broad-leaved		Total	
	40 DAS	60 DAS	40 DAS	60 DAS	40 DAS	60 DAS	40 DAS	60 DAS
Sowing dates (P)								
15th June	2.65 (8.17)	4.27 (19.28)	1.18 (0.98)	1.45 (1.96)	1.71 (2.83)	3.02 (9.63)	3.20 (11.98)	5.34 (30.87)
30th June	3.09 (10.74)	4.74 (23.53)	1.30 (1.27)	1.46 (2.00)	1.96 (3.73)	3.42 (12.11)	3.75 (15.74)	5.95 (37.65)
15th July	3.84 (15.48)	5.56 (31.90)	1.56 (2.05)	1.67 (2.64)	2.34 (5.47)	3.97 (16.32)	4.65 (23.00)	6.97 (50.87)
LSD (p=0.05)	0.15	0.18	0.08	0.07	0.07	0.09	0.13	0.12
Weed Management (W)								
Soil solarization 25 DBS *fb* hand weeding at 30 DAS	2.93 (8.48)	4.88 (23.71)	1.27 (1.15)	1.60 (2.10)	1.83 (2.94)	3.70 (13.40)	3.55 (12.57)	6.26 (39.22)
Mulching with paddy straw 5 t/ha *fb* hands weeding at 30 DAS	3.05 (9.13)	5.08 (25.65)	1.29 (1.19)	1.62 (2.16)	1.92 (3.27)	3.98 (15.53)	3.69 (13.59)	6.58 (43.34)
Pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS	2.16 (4.57)	3.88 (14.86)	1.07 (0.67)	1.19 (0.96)	1.37 (1.45)	2.66 (6.74)	2.59 (6.70)	4.75 (22.56)
Pendimethalin 1000 g/ha PE *fb* intercultural at 30 DAS	2.48 (6.06)	4.61 (21.18)	1.20 (.97)	1.39 (1.46)	1.70 (2.46)	3.22 (10.02)	3.08 (9.50)	5.71 (32.66)
Imazethapyr 100 g/ha PoE 20DAS *fb* Intercultural at 30 DAS	2.32 (5.28)	4.45 (19.75)	1.11 (0.76)	1.24 (1.10)	1.51 (1.85)	2.93 (8.29)	2.81 (7.89)	5.38 (29.14)
Hand weeding twice at 20 and 40 DAS	3.50 (12.02)	3.60 (12.71)	1.50 (1.78)	0.84 (0.23)	2.23 (4.57)	2.35 (5.19)	4.30 (18.36)	4.27 (18.14)
Weedy check (control).	5.9 (34.72)	7.51 (56.47)	1.98 (3.52)	2.80 (7.38)	3.45 (11.52)	5.45 (29.65)	7.05 (49.75)	9.65 (93.50)
LSD (p=0.05)	0.20	0.21	0.10	0.10	0.09	0.16	0.18	0.21

Original values were subjected to square root transformation. Figures in parentheses are the original values. DAS = date of sowing; DBS = days before seeding, *fb* = followed by; PE = pre-emergence application; PoE = post emergence application

Table 3. Effect of sowing dates and integrated weed management treatments on weed control efficiency (WCE), soybean plant growth parameter and yield (pooled data of 2021-2022)

Treatment	Weed control efficiency (%)		Plant height (cm)	Branches /plant	Dry matter (g/plant)	LAI	Root nodules/ plant	Dry wt. of nodules	Seed yield (t/ha)	Stover yield (t/ha)
	40 DAS	60 DAS	at harvest	at harvest	60 DAS	60 DAS	60 DAS	60 DAS		
Sowing dates (P)										
15th June	71.42	61.65	59.54	3.86	27.22	2.73	40.42	0.41	2.01	2.44
30th June	68.04	58.17	54.83	3.38	24.65	2.48	35.53	0.35	1.72	2.33
15th July	59.52	52.61	48.92	2.87	19.48	1.95	29.45	0.31	1.25	2.13
LSD (p=0.05)	-	-	1.94	0.15	1.08	0.13	1.49	0.015	0.09	0.12
Weed Management (W)										
Soil solarization 25 DBS *fb* hand weeding at 30 DAS	75.11	58.01	54.16	3.30	22.62	2.31	31.68	0.33	1.53	2.18
Mulching with paddy straw 5 t/ha *fb* hands weeding at 30 DAS	73.02	53.46	52.96	3.22	21.82	2.16	28.16	0.30	1.38	2.02
Pendimethalin 1000 g/ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS	86.99	76.00	59.48	3.77	25.73	2.65	42.21	0.42	2.05	2.66
Pendimethalin 1000 g/ha PE *fb* intercultural at 30 DAS	81.48	65.03	56.27	3.48	23.38	2.42	35.32	0.35	1.74	2.40
Imazethapyr PoE 100 g/ha 20 DAS *fb* Intercultural at 30 DAS	84.58	69.08	56.99	3.58	24.14	2.52	37.99	0.38	1.91	2.59
Hand weeding twice at 20 and 40 DAS	63.12	80.75	61.21	3.95	28.64	2.72	48.07	0.45	2.21	2.78
Weedy check (control).	0.00	0.00	39.95	2.28	20.16	1.90	22.52	0.26	0.81	1.49
LSD (p=0.05)	-	-	2.82	0.22	0.96	0.19	1.95	0.02	0.07	0.16

DBS= days before seeding; *fb* = followed by; PE = Pre-emergence application; PoE = Post emergence application

growth conditions, including adequate space, light, moisture, and nutrients, as well as enhanced accumulation of photosynthates, thereby promoting superior growth, development, and spatial distribution of the soybean crop (Samudre *et al*. 2019, Chouhan and Verma 2023, Jadon *et al*. 2019).

It is concluded that the early sowing of soybean (on June 15) and application of pendimethalin 1000 g/ ha PE *fb* imazethapyr 100 g/ha PoE at 20 DAS, provides optimal weed control and enhances the soybean growth attributes and yield under the rainfed conditions in Nagaland.

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RESEARCH ARTICLE

Efficacy of herbicides' combinations in managing weeds and on crop productivity and soil microbial safety in sugarcane fields of Kenya

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ABSTRACT

The efficacy of herbicides combinations in managing annual weed flora and to assess their effect on soil microbes in sugarcane (*Saccharum officinarum L.*) were evaluated during 2018-19 and 2019-20 cropping seasons at the Kenya Agricultural and Livestock Research Organization in Kisumu, Kenya. The sugarcane (variety KEN 83-737) field with natural weed infestation was used for experimentation in a randomized complete block design (RCBD) with four replications. The tested treatments included: post-emergence applications (PoE) of metribuzin 960g/ha; diuron + hexazinone + sulfometuron-methyl 603 + 170 + 14.5 g/ha; trifloxysulfuron-sodium + ametryn 1097 + 27.8 g/ha; diuron + hexazinone 1170 + 330 g/ha; untreated/weedy check, and hand hoeing twice at 30 and 45 days after sugarcane planting (DAP). The weed density, sugarcane tiller numbers, cane height, millable stalks, and cane yield were significantly different ($p < 0.05$) across the treatments. All herbicides and the hand hoeing twice proved effective for weed control, resulting in higher sugarcane yields. The combination of diuron, hexazinone, and sulfometuron-methyl resulted in the best weed control, albeit with slight phytotoxicity. The herbicides exhibited varying levels of efficacy in weed control, phytotoxic effects on sugarcane, and impacts on microbial composition and cane yield. Diuron + hexazinone 1170 + 330 g/ha PoE recorded the highest net returns amongst the tested treatments.

Keywords: Diuron + hexazinone, Diuron + hexazinone + sulfometuron-methyl, Metribuzin, Phytotoxicity, Sugarcane, trifloxysulfuron-sodium + ametryn, Weed management

INTRODUCTION

Sugarcane (*Saccharum officinarum L.*) is a globally important agro-industrial crop (Singh *et al.* 2015). It is a main source of sugar and bio-energy, accounting for over 70% of the raw table sugar supply in the world. In Kenya, it ranks as one of the top six commercial crops alongside tea, cut flowers, vegetables, coffee, and maize. Sugarcane plays a key socio-economic role in the country. It is used as raw material in sugar and ethanol production, the burning of bagasse as an electricity source, and as animal feed, among other uses (Castro *et al.* 2019).

Weeds affect yields, quality, harvesting, and sugarcane processing, resulting in huge yield losses (Castro *et al*. 2019, Mandal *et al.* 2020, Patel *et al.* 2024). Weeds in sugarcane production are more problematic than in other crops because sugarcane is planted with relatively wider spacing, and the crop has a relatively slow growth at the initial stages with 30 days to germinate and 60 to 75 days to develop a full canopy (Anusha and Rana 2016). The loss to sugarcane due to weed competition, combined with the cost of weed management, runs into millions (Barceló and Cruz 2015). The losses could be due to competition or indirectly caused by reduced quality, increased costs during operations, such as harvesting and land preparation, or may harbour insect pests and diseases (Rono *et al.* 2015). Weeds are heavy feeders and extract a high amount of nutrients from the soil, while others, such as the morning glory (*Ipomoea purpurea)*, twine around the cane stalks, bending and damaging their tops, resulting in a 20-25% loss (Rono *et al.* 2015).

The use of herbicides to control weeds in sugarcane has been recommended as an alternative to hoeing due to their efficacy and as a cheaper alternative (Castro *et al.* 2019). Both pre- and post-emergence herbicides have been recommended for weed control in sugarcane farming in Kenya. However, these herbicides control specific weed species and may affect non-target soil microorganisms as well as have phytotoxic effects on the sugarcane crop. To be more effective, herbicide mixtures that have both additive and synergistic

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effects are available. However, herbicides' efficacy, their effect on non-target microorganisms and arthropods, and their levels of phytotoxicity on sugarcane are major concerns. Thus, the current study was conducted to evaluate the efficacy of various herbicide combinations in managing weeds and increasing sugarcane yield, as well as to assess their phytotoxicity on sugarcane and their effect on soil microbes.

MATERIALS AND METHODS

A two-year field study was conducted during the long rain cropping seasons of 2018-19 and 2019-20 at the Kenya Agricultural and Livestock Research Organization- Sugar Research Institute (KALRO-SRI) in Kibos, Kisumu County, Kenya. The site is situated at an elevation of 1,250 m above sea level (0°21'01.0"S 34°49'17.0"E), with a mean annual temperature of 19.7°C and average annual precipitation of 1,900 mm. The average soil pH of the field was 5.3, with organic carbon of 1.24%, and nitrogen of 0.15%

The experiment was laid out in a randomized complete block design (RCBD) with four replications. The experiment consisted of six treatments, *viz.* post-emergence application (PoE) of metribuzin 960 g/ha, diuron + hexazinone + sulfometuron-methyl 603 + 170 + 14.5 g/ha, trifloxysulfuron-sodium + ametryn 1097 + 27.8 g/ha, diuron + hexazinone 1170 + 330 g/ha, untreated/ weedy check, and hand hoeing twice at 30 days and 45 days after sugarcane planting (DAP).

Clean seed cane material of variety KEN 83-737, acquired from the KALRO-SRI farm at Kibos was planted into 5-meter-long furrows spaced 1.2 metres apart. The setts were planted end-to-end in the furrows, thus translating to a seed rate of 7 t/ha. Di-ammonium phosphate (DAP) (18:46:0) fertilizer was basally applied at the time of planting at the rate of 100 kg/ha, and topdressing was done at 5 months of age using Calcium Ammonium Nitrate (CAN) at 100 kg/ ha.

The herbicides were applied using a hand-operated Jacto HD 550 knapsack sprayer, calibrated to deliver 400 L/ ha of water with an effective spray swath of 2m, and fitted with a flat fan nozzle. Spraying was done at 30 DAP (when weeds were at the four to six-leaf stage).

Weed counts were established just before spraying and at 7, 14, and 30 days after herbicide application (DAA) to establish the efficacy. Weed species counts were done in four randomly placed 0.25 m^2 quadrats. Weeds were grouped into three categories, *i.e.* broad-leaved, grasses or sedges, and weed counts are expressed as weed density (no./m^2).

In the 2019/2020 testing year, soil samples (0-15 cm depth) from each experimental plot were randomly collected using a trowel and later mixed thoroughly to make a composite representative sample for fungal and bacterial populations enumeration. The samples were collected before spraying, at 7, 14, 21, and 60 DAA, and during harvest. A sub-sample of approximately 150 grams per sample was placed in a freezer at 4°C until microbial analysis (bacteria and fungi) was conducted. Enumeration of microbes was done on agar plates following the serial dilution technique and pour plate method (Koch *et al.* 2014). The bacteria were analyzed in nutrient agar, whereas fungi were analyzed on Rose Bengal agar media with streptomycin (Singh *et al.* 2017) and expressed as colony-forming units/gram (cfu/g).

At harvest, the number of millable stalks in the net plot (2 inner rows) per treatment was counted and expressed as numbers per ha by extrapolation. Cane yield per treatment was determined by weighing all millable stalks per plot using a salter scale and extrapolating to kg/ha. The % yield change was calculated by comparing the yield per treatment to the yield of the weedy check.

Five stalks were randomly selected per plot, and the height of each stalk (cm) from the ground to the dewlap leaf was measured using a tape measure. On the same stalks, the number of internodes per stalk was determined by counting, and total sugars (brix) were measured using a handheld refractometer to estimate the effect on sucrose content at harvest.

The phytotoxic effects of the herbicide treatments were assessed through visual observation of symptoms, including chlorosis (yellowing), stunting, leaf scorching, and epinasty. Evaluations were conducted at appropriate intervals using a visual rating scale ranging from 0 to 100%, where 0% indicated no visible phytotoxic symptoms, and 100% represented complete plant death (Castro *et al.* 2019). The net returns were calculated by subtracting the varying costs of production from the gross returns (average yield in the two seasons and prevailing price per ton).

The data on the weed density was transformed into Log (2 + value) before analysis. The data was then subjected to analysis of variance by t-test at 5% probability using the Statistical Analysis Software (SAS Version 9.4). The means were then compared and separated using Fisher's least significant difference (LSD) at p=0.05.

RESULTS AND DISCUSSION

Effect on weeds

The major weed flora observed in the experimenta field were: grasses; *Panicum* spp., *Setaria* spp., *Rhottboelia exaltata*, and *Digitaria* spp. constituting 12%, 8%, 5%, and 2%, respectively. Of the total weeds recorded; broad-leaved weeds (BLWs) were: *Ageratum conyzoides* (15%), *Bidens pilosa* (21%), *Comellina benghalenis* (7%), *Euphoria hirta* (5%), *Galinsoga parviflora* (3%), *Amaranthus* spp. (2%) and *Datura stramonium* (2%). *Cyperus esculentus* was the only sedge with 23% relative density. Broad-leaved weeds constituted over 46% of the total weed density. Similar dominance of broad-leaved weeds as the most predominant in sugarcane was reported earlier (Rasker 2004).

The treatments had a significant (p=0.05) effect on the BLWs, grasses and sedges in the three years **(Table 1).** Hand hoeing had the best weed control (100%) in the three seasons. The highest BLW density was recorded in the weedy check. Among the herbicides, a combination of diuron + hexazinone + sulfometuron-methyl 603 + 170 + 330 g/ha PoE caused the best control of broad-leaved weeds. On the other hand, the diuron + hexazinone + sulfometuron-methyl 603 + 170 + 14.5 g/ha PoE, trifloxysulfuron-sodium + ametryn 1097.3 + 27.8 g/ha PoE and diuron + hexazinone applied 1170 + 330 g/ha PoE, significantly reduced the grassy weed flora. Only hoeing gave appreciable control of sedges. Herbicide mixtures have been known to perform better than single-molecule herbicides, though sometimes expensive (Barceló and Cruz 2015). In a trial in Egypt, post-emergence herbicides containing triclopyr and clomazone, and hand hoeing at 30 and 45 DAP had a significant effect on weeds in comparison to the untreated control (Mohamed and Marzouk 2021).

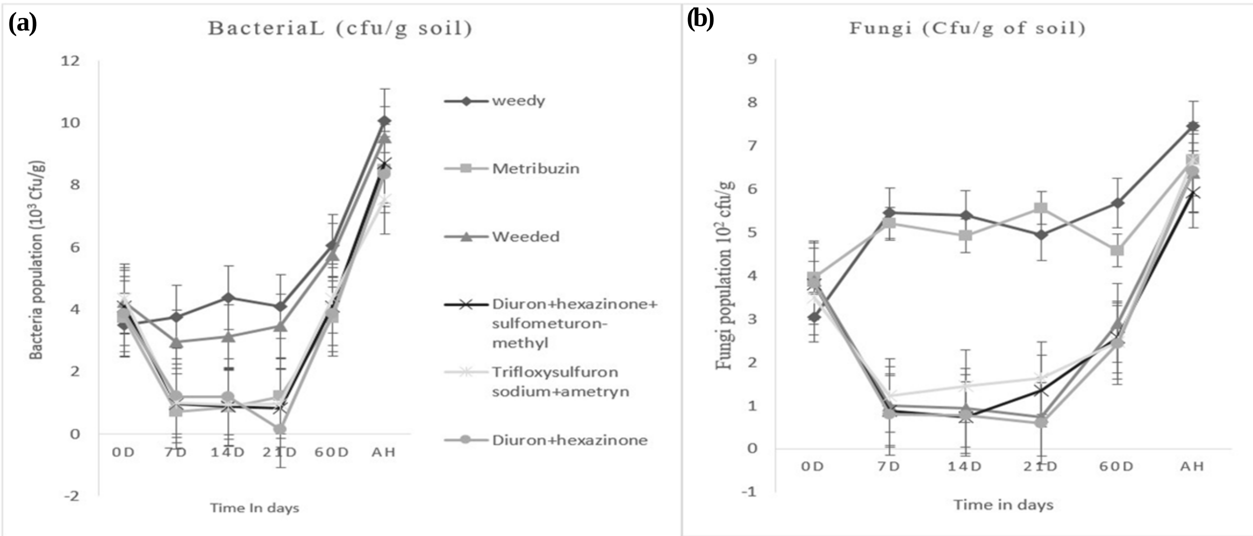
Bacterial population: Different herbicide treatments had no significant effect on the bacterial populations in the soil as reported earlier by Singh *et al.* (2017). However, the weedy check and the plot with hoeing twice treatment had higher bacterial colony-forming units than the herbicide-treated plots. From the 21st day after treatment, all the bacterial populations increased to peaks of 7.5 to 9.52 x10^3cfu/g of soil from diuron + hexazinone and the weedy check, respectively **(Figure 1a).**

Fungal population: Fungal counts drastically declined within the first seven days after treatment, and picked up gradually from the fourteenth day. The fungi in the hoeing twice and weedy check treatments were significantly different (P=0.05) from the herbicide-treated plots from the 7th to 60th day after treatment but was not different at harvesting (**Figure 1b).** This concurs with findings by Singh *et al.* (2017) who reported a decline in the fungal population in India after the use of halosulfuron + metribuzin at different doses. The interaction between herbicides-cultivars and season influenced rhizospheric soil variables in Brazil's sugarcane (Faria *et al.* 2018). Microorganisms were stressed (low respiratory levels) when diuron was used at high concentrations, but this did not happen when lower levels of diuron mixed with hexazinone were used (Faria *et al.* 2018). According to Da Silva *et al.* (2014), sugarcane varieties vary in their capacity to associate with soil microorganisms, leading to varied responses of the microbes to the herbicides.

Table 1. Efficacy of different weed management treatments on density (no./m^2) of broad-leaved weeds (BLWs), grasses and the sedge in the two seasons

Treatment	Rate (kg or l/ha formulated product)	Weed density (log2 + value/m^2)					
		BLWs		Grasses		Sedge	
		2018-19	2019-20	2018-19	2019-20	2018-19	2019-20
Metribuzin 960 g/ha	2.0	0.9(5.8)	0.8(4.8)	0.6(2.3)	0.5(1.2)	1.9(74.2)	1.5(30.2)
Diuron + hexazinone + sulfometuron-methyl 603 + 170 + 14.5 g/ha	1.0	0.4(0.6)	0.4(0.5)	0.4(0.5)	0.4(0.5)	1.8(68)	1.2(14.0)
Trifloxysulfuron-sodium + ametryn 1097.3 + 27.8 g/ha	1.5	0.6(2.3)	0.7(3.1)	0.5(1.5)	0.4(1.5)	1.7(50.3)	1.4(32.0)
Diuron + hexazinone1 170 + 330 g/ha	2.5	0.6(2.0)	0.6(1.9)	0.5(1.5)	0.4(0.5)	1.9(80.2)	1.3(21.2)
Weedy		2.1(130.5)	0.9(6.3)	0.6(2.4)	0.6(2.3)	2.1(110.9)	1.6(40.6)
Hand hoeing twice		0.3(0.0)	0.3(0.0)	0.3(0.0)	0.3(0.0)	0.3(0.0)	0.3(0.0)
Cv (%)		30.8	40.9	28.3	26.5	9.7	22.9
LSD (p=0.05)		0.4	0.4	0.2	0.2	0.2	0.4

LSD: least significant difference at the 5% level of significance, CV: Coefficient of variation. The weed density was log transformed (Log2 + value)



D: days, AH: at harvest

Figure 1. Effect of herbicide treatments on (a) bacteria and (b) fungi populations before and at different times after treatment application in the 2019/2020 season

Table 2. Effect of tested weed management treatments on sugarcane quality (brix), growth parameters, yield and net return

Treatment	Brix		No. of Stalks ('000/ha)		Height (cm)		No. of Internodes		Cane yield (t/ha)			Net returns (USD/ha)
	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	% change	
Metribuzin 960 g/ha	21.6	20.4	89.3	164.5	199.4	277.4	28.5	26.3	55.4	147	12	2419
Diuron + hexazinone + sulfometuron-methyl 603 + 170 + 14.5 g/ha	20.9	20.4	100.0	149.3	210.6	279.3	32.8	26	53.9	146	11	2394
Trifloxysulfuron-sodium + ametryn 1097.3 + 27.8 g/ha	21.2	20.9	131.0	160.3	216.4	286.3	31.0	28.8	60.4	143	13	2451
Diuron + hexazinone 1170 + 330 g/ha	21.8	20.1	110.0	175.3	215.0	288.6	30.8	26	65.9	159	25	2737
Weedy	20.6	20.1	104.0	155.5	200.2	261.6	30.3	27.0	51.0	129	0	2261
Hand hoeing twice	21.6	20.4	103.0	168.3	205.3	258.2	31.3	25.8	57.0	163	22	2442
Cv (%)	3.2	1.7	18.5	16.6	8.7	7.4	7.2	7.1	21.9	18.1	-	-
LSD(p=0.05)	1.0	0.5	29.6	40.6	27.1	30.7	3.3	2.8	8.9	42.6	-	-

LSD: least significant difference at the 5% level of significance, CV: Coefficient of variation

Sugarcane growth parameters and yield

The sugarcane yield attributes varied significantly (p=0.05) across the various treatments, except for the millable stalks in 2019-20 and the cane height during both years of study (**Table 2**). The weeds had a quality and quantity yield loss on sugarcane. Weedy check recorded the lowest cane yields of 51 and 128 t/ha in the 2018-19 and 2019-20 seasons, respectively. The unrestricted growth of weeds in sugarcane at the early stages caused yield losses of up to 22%. Similarly, the lowest brix (total sugars) was recorded in the weedy check.

All the treatments had an increase in yield when compared to the weedy check. In the first season, the highest yield was recorded with diuron + hexazinone, whereas in the second season, the highest yields was with hand hoeing twice. Diuron + hexazinone treatment had the highest percent yield increase of 25%, followed by hand hoeing twice with a 22% yield increase. The effect of weeds on sugarcane yields was attributed to competition for moisture, nutrients, and light during growth (Barceló and Cruz 2015, Anusha and Rana 2016). The higher yields observed are attributed to decreased weed biomass, leading to improved plant growth and sugarcane yields (Singh *et al.* 2015, Ali *et al.* 2018). The highest net returns (US $ 2737/ha or 410,600 shillings/ha) were recorded with diuron + hexazinone 1170 + 330 g/ha PoE, while the least (US $ 2261/ha or 339,166 shillings/ha) was recorded with weedy check.

Herbicide phytotoxicity on sugarcane

There were no major phytotoxic effects in terms of scorching, necrosis, hyponasty, or epinasty due to tested herbicides. However, moderate to slight chlorosis and stunting were noted with diuron + hexazinone + sulfometuron-methyl and diuron +

hexazinone at 7 DAA, which recovered fully by the 60th day after application (data not presented in this paper). A similar response was observed with diuron + hexazinone treatment in Brazil, but the effect varied across varieties (Castro *et al.* 2019). Cultivars exhibited differential susceptibility to varying doses of ametryn + trifloxysulfuron-sodium. Cultivar RB855113 had the highest phytotoxicity 28 days after herbicide application (Ferreira *et al.* 2005; Da Silva *et al.* 2014). Trifloxysulfuron-sodium was more tolerated by most varieties as compared to ametryn and its combinations. However, higher doses of the trifloxysulfuron-sodium enhanced the growth of sugarcane (Da Silva *et al.* 2014). A similar effect to that from diuron + hexazinone + sulfometuron-methyl was reported in sugarcane fields treated with sulfometuron-methyl (Assis *et al.* 2018).

It is concluded that the highest sugarcane yield and net returns were recorded under the diuron + hexazinone 1170 + 330 g/ha PoE and hence can be recommended for managing weeds and realizing higher productivity of sugarcane in Kenya.

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RESEARCH ARTICLE

Bio-efficacy of saflufenacil + dimethenamid-P as pre-emergent herbicide to manage weeds in sugarcane

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ABSTRACT

The growth and productivity of sugarcane is known to be affected by uncontrolled weed competition at crop establishment stage due to reduced availability of resources. During spring season (February to December) of 2018 and 2019, a field study was conducted at Punjab Agricultural University, Ludhiana, Punjab, India using a randomized complete block design with three replications. The objective of the study was to evaluate the effect of pre-emergence application (PE) of different doses of ready-mix saflufenacil 68 g/L plus dimethenamid-P 600 g/L (saflufenacil + dimethenamid-P) on weed control and sugarcane productivity. The premix of saflufenacil + dimethenamid-P at 835 g/ha as PE resulted in 85.2-87.6%, 68.8-70.2% and 72.0-72.9% weed control efficiency of grasses, broad-leaved weeds and sedges, respectively at 60 days after application. The saflufenacil + dimethenamid-P at 835 g/ha application resulted in 20.8-20.9% more millable canes and 62.3-65.2% higher cane yield than untreated control demonstrating its efficacy in managing diverse weed flora at early crop establishment stage resulting in statistically similar cane yield to weed free check. However, there is a need of post-emergence herbicide application in sugarcane after pre-emergence herbicide application to achieve adequate weed control and improved productivity of sugarcane in Indian sub-tropics.

Keywords: Dimethenamid-P, Pre-emergent herbicide, Saflufenacil, Sugarcane, Weed management

INTRODUCTION

Sugarcane is an important cash crop in India, grown over 5.7 million hectares, with total production of 446.4 million tons and an average productivity of 79.0 tons per hectare (MOA 2024). It contributes nearly 78% to the global sugar base and plays a vital role in ethanol production (Gowtham *et al.* 2019, Singh *et al.* 2021). As the second-largest agro-industry in India, after textiles, the sugar industry supports around 6 million farming families (Verma 2015). By 2030, the sugar demand is projected to reach 36 million tons, nearly three times of the current production (12.1 million tonnes) (Ballyan *et al.* 2015). Bridging this considerable gap will require improvements in productivity and sugar recovery from the existing sugarcane area. Sugarcane is a labor-intensive crop, requires approximately 3,300 man-hours for the completion of recommended cultural practices (Arumuganathan 2022). Due to the slow initial growth, the inter-row spaces remain uncovered by the canopy that creates favorable environment for rapid weed growth. Frequent irrigation and fertilizer applications further increase weed population in sugarcane (Krishnaprabhu 2020). Weeds can severely reduce the cane yield by 12% to 83%, while quality and sugar recovery by 25% to 80% (Khan 2015). El-Shafai *et al.* (2010) reported weed competition can cause a 32% reduction in millable stalks, 15% decrease in stalk thickness and 31% reduction in sugar yield over weed-free plots. India suffers a cane yield loss of around 25 million tons annually, equivalent to a loss of 2.5 million tonnes of sugar, which is worth approximately Rs. 1500 crores (Takin *et al.* 2014).

Weed management is a crucial operation in sugarcane cultivation, after selection of variety and irrigation management (Jaiswal *et al.* 2024). Effective and timely control of weeds is essential for achieving higher productivity in sugarcane crop and the most used method is pre-emergence herbicide application, as it ensures a prolonged residual effect and control effectiveness during the critical period of competition with the sugarcane crop (Singh and Kumar 2013, de Castro *et al.* 2024). In northwest part of India, the critical period for crop-weed competition has been identified up to 120 days after planting in sugarcane (Bhullar *et al.* 2008). Weeds in sugarcane can be managed through manual, mechanical or chemical methods (Danawale *et al.* 2012). Three manual

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hoeing are recommended at the tillering phase to control weeds below the threshold level (Singh and Kumar 2013,). However, the labor shortage at the critical crop-weed competition period and high labor costs are major constraints that limit the adoption of manual weeding among sugarcane farmers (Pratap *et al.* 2013). The use of herbicides offers an excellent alternative to manual weeding, being both cost-effective and less labor-intensive. In northwest part of India, pre-emergence application (PE) of herbicides such as atrazine 1.0 kg/ha or metribuzin 1.4 kg/ha or diuron 1.6 kg/ha or sulfentrazone + clomazone 0.7 + 0.75 kg/ha can effectively control all annual weeds in sugarcane (Singh *et al.* 2001; Anonymous 2025). For managing *Cyperus rotundus* and *Ipomoea* spp., a post-emergence spray of 2,4-D sodium salt 1.6 kg/ha is recommended. However, continuous use of the same herbicides with similar modes of action can lead to weed shifts (tough to control such as *Brachiaria reptans, Ipomoea nil, etc.*) and the evolution of herbicide-resistant weeds along with potential environmental concerns (Bhullar *et al.* 2008, 2012; de Castro *et al.* 2024). Therefore, the research and commercialization of new alternative herbicides with novel mechanism/mode of action have become increasingly urgent in present scenario. One premix formulation containing saflufenacil and dimethenamid-P was developed for pre-emergence control of weeds in sugarcane, and the field performance of saflufenacil plus dimethenamid-P against complex weed flora in sugarcane needs to be investigated. Therefore, this study was conducted to determine the effective use rates of saflufenacil 68 g/L plus dimethenamid-P 600 g/L (hereafter, saflufenacil + dimethenamid-P) applied as pre-emergent herbicide in sugarcane to manage weeds and improve sugarcane productivity.

MATERIALS AND METHODS

A field experiment was carried out during the spring season (February to December) of 2018 and 2019. The research was conducted at the Agronomy Research Farm of Punjab Agricultural University, Ludhiana, Punjab, India (30°56’N latitude, 75°52’E longitude and at 247 meters above MSL), situated in the northwestern Indo-Gangetic Plains within a subtropical climatic zone. This region is characterized by a semi-arid, subtropical climate, featuring hot, dry summers from April to June, followed by a humid monsoon period between July and September. The winter season starts mildly in October and November and becomes colder through December to February. The area typically receives between 500 and 750 mm of rainfall annually, with nearly 75% of it occurring during the southwest monsoon from July to September. The soil at the test site is sandy loam in texture, with a neutral pH (7.5) and low electrical conductivity (0.13-0.18 dS/m). The organic carbon content is medium (0.39%), while the soil is low in $KMnO_4$-N (223.4 kg/ha), high in Olsen-P (29.9 kg/ha) and high in NH_4OAc-K (337 kg/ha).

The treatments in the field experiment consisted of ready-mix/premix of saflufenacil + dimethenamid-P at 501, 668 and 835 g/ha, saflufenacil 70% WG (hereafter, saflufenacil) at 70 g/ha, dimethenamid-P 720 g/L EC (hereafter, dimethenamid-P) at 600 g/ha, metribuzin 70% WP (hereafter, metribuzin) at 525 g/ha, 2,4-D dimethylamine salt 58% SL (hereafter, 2,4-D dimethylamine salt) at 3500 g/ha, weed-free check and an untreated control. The experiment was laid out in a randomized complete block design with three replications. Sugarcane cv. Co 118 and CoJ 88 were used in the study during 2018 and 2019, respectively. Co 118 is an early-maturing cultivar and CoJ 88 a mid-late maturing cultivar. Both cultivars are frost-resistant. The planting was done on April 22, 2018 and March 1, 2019, at a seed rate of 7.50-8.75 t/ha with 75 cm row spacing using the trench method. Each plot measured 6.0 m × 4.5 m (27 m^2), with six rows. Irrigation was applied on the same day of planting to create optimal moisture conditions for the pre-emergence herbicide application. Herbicides were sprayed using a knapsack sprayer with a flat fan nozzle on April 25, 2018 and March 3, 2019, during the first and second season, respectively. In the weed-free treatment, weeds were manually removed using *khurpa* or mechanically controlled with a *kasuala* or improved wheel hand hoe. The recommended cultivation practices were followed to raise the crop, except weed management. The seedbed was prepared by ploughing once with a disc harrow, followed by two ploughings with a cultivator, with each ploughing followed by planking. The crop was fertilized with 150:30 kg N and P/ha through 325 kg urea/ha and 187 kg single super phosphate/ha, where the full dose of P was applied at the time of sowing. Nitrogen was applied in two splits, *i.e.*, one half dose top dressed alongside the crop rows with first irrigation after emergence and remaining half dose alongside cane rows after one month. To prevent the crop from lodging, earthing up was done at the end of June, before the onset of the monsoon. Crop was prop up in the end of august by using the trash-twist method. The crop was harvested manually on January 2nd, 2019 and February 10th, 2020.

Data of plant height at 60 DAA, number of tillers at 60 DAA, cane length, number of millable canes and cane yield at harvest were recorded. Data on weeds was recorded with quadrat (50 × 50 cm) from two locations in each plot at 20 and 60 days after application (DAA). Bio-efficacy in terms of weed control was recorded by taking observations of weed density and biomass. Species wise weed density was recorded at 20 and 60 DAA while biomass of weed species was observed at 60 DAA only. To analyse and interpret weed density and biomass, the average of both quadrats was converted into numbers per square meter (no./m^2) and grams per square meter (g/m^2), respectively. Weed control efficiency was calculated based on weed biomass observed in untreated check at 60 DAA. Weed control efficiency was calculated using the formula suggested by (Mani *et al.* 1973), as shown below:

$$\text{Weed control efficiency (\%)} = \frac{\text{WBc} - \text{WBt}}{\text{WBc}} \times 100$$

where, WBc is the weed biomass in untreated control and WBt is the weed biomass in treated plot. Analysis of variance was performed to assess the efficacy of ready-mix of saflufenacil + dimethenamid-P against complex weed flora in sugarcane. Data were analysed using the General Linear Model (GLM) procedure in IBM SPSS Statistics 22. To normalize the variance of weed data, square root transformation was conducted before performing ANOVA. To determine significant differences between means, the Fisher's Least Significant Difference (LSD) test was employed at a 5% probability level (p=0.05).

RESULTS AND DISCUSSION

Effect on weeds

During both the years of study, the experimental field was infested with complex weed flora comprising of grasses such as: *Echinochloa colona, Eleusine indica, Dactyloctenium aegyptium, Digitaria sanguinalis, Acrachne racemosa;* sedges such as *Cyperus rotundus* and broad-leaved weeds such as *Ipomoea nil, Trianthema portulacastrum, etc.* There were no weeds prior to pre-emergence application. Density of grasses, broad-leaved weeds and sedges at 20 and 60 DAA were significantly influenced by weed control treatments over untreated control. At 20 DAA, saflufenacil + dimethenamid-P 501 to 835 g/ha and standard herbicides (saflufenacil 70 g/ha and dimethenamid-P 600 g/ha) significantly controlled all grasses and broad-leaved weeds over untreated control during both the years of study (**Table 1**). All the herbicidal treatments recorded 100% weed control efficiency for grasses and broad-leaved weeds at 20 DAA. The density of *C. rotundus* was significantly lower with saflufenacil + dimethenamid-P 668 to 835 g/ha as compared to its lower dose of 501 g/ha at 20 DAA. Saflufenacil 70 g/ha, dimethenamid-P at 600 g/ha and metribuzin at 525 g/ha were not effective on *C. rotundus* while 2,4-D dimethyl amine salt at 3500 g/ha resulted in significantly lower density over other herbicide treatments (**Table 1**). The growth of newly germinated weed seeds or seedlings may be inhibited with the application of ready-mix pre-emergence herbicides due to their synergistic effect of the combined molecules. Therefore, during the initial

Table 1. Effect of weed management treatments on weed density (no./m^2) at 20 DAA in sugarcane

Treatment	*Echinochloa colona*		*Eleusine indica*		*Dactyloctenium aegyptium*		*Digitaria sanguinalis*		*Acrachne racemosa*		*Cyperus rotundus*		*Ipomoea nil*		*Trianthema portulacastrum*	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Saflufenacil + dimethenamid-P 501 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	2.44 (5)	2.47 (6)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Saflufenacil + dimethenamid-P 668 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.82 (2)	1.89 (3)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Saflufenacil +dimethenamid-P 835 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.39 (1)	1.41 (1)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Saflufenacil 70 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	3.55 (12)	3.66 (13)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Dimethenamid-P 600 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	3.65 (12)	3.69 (13)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Metribuzin 525 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	3.51 (11)	3.53 (12)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
2,4-D dimethyl amine salt 3500 g/ha	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	0.67 (1)	1.27 (1)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Weed free check	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Untreated control	3.00 (8)	2.64 (6)	2.31 (4)	2.44 (5)	3.87 (14)	3.65 (12)	3.55 (12)	3.46 (11)	2.44 (5)	2.38 (5)	3.87 (14)	3.74 (13)	1.99 (3)	2.23 (4)	2.00 (3)	2.23 (4)
LSD (p=0.05)	0.10	0.11	0.07	0.12	0.07	0.12	0.13	0.08	0.12	0.07	0.23	0.20	0.15	0.13	0.01	0.13

*Data is subjected to square root transformation ($\sqrt{x+1}$). Figures in parentheses are means of original values in round figures DAA = days after herbicide application period of crop growth, total weed density was significantly less as compared to untreated control. Bhullar *et al.* (2008) observed the synergistic effect of pendimethalin with metribuzin/atrazine on weed control in spring planted sugarcane.

Later at 60 DAA, weeds started emerging in all experimental plots receiving herbicides. However, application of saflufenacil + dimethenamid-P at 835 g/ha resulted in 66.7% and 65.6%, 48.6% and 45.9%, 63.2% and 60.0%, 72.4% and 70.0%, 36.8% and 38.4% lower grass weeds, *viz. E. colona, E. indica, D. aegyptium, D. sanguinalis* and *A. racemose*, respectively, and 40.9% and 39.9%, 66.2% and 65.4% reduced density of broad-leaved weeds, *viz. I. nil* and *T. portulacastrum*, respectively over untreated control during first and second year, respectively (**Table 2**). Further, density of sedges at 60 DAA in plots treated with saflufenacil + dimethenamid-P 835 g/ha was 34.4% and 33.2% less than untreated control during 2018 and 2019, respectively which was statistically similar to 2,4-D dimethyl amine salt at 3500 g/ha. Earlier researchers also reported that integrated weed control methods comprising of pre- and post-emergence herbicides with mechanical weeding resulted in the long-term weed control efficiency as compared to alone pre-emergence herbicide application (Raskar 2004, Singh *et al.* 2008, Bhullar *et al.* 2012, Pratap *et al.* 2013). The pre-emergence application of ready-mix of saflufenacil + dimethenamid-P was also labeled for its residual control of several annual grasses, broad-leaved weeds, and sedges in crops such as grain sorghum, soybean and field corn (BASF 2025). Pratap *et al.* (2013) reported the lowest density and biomass of total weeds in sugarcane ratoon with hand weeding thrice at 30, 60 and 90 days after planting which was at par with integrated treatment of metribuzin at 0.88 kg/ha as pre-emergence followed by one hand weeding at 45 days and spray of 2,4-D Na salt 0.75 kg/ha at 2-4 leaf stage of broad-leaved weeds. Further, saflufenacil at 70 g/ha and dimethenamid-P at 600 g/ha at 60 DAA were found to be less effective when compared to their pre-mix herbicide in this study. Bhullar *et al.* (2008) also reported that tank-mix of pendimethalin 0.75 kg/ha either with metribuzin 0.875 kg/ha or atrazine 0.75 kg/ha than standalone application of pendimethalin 1.125 kg/ha and atrazine 1.0 kg/ha were very effective for control of *Brachiaria reptans* in spring sugarcane. In Brazil, tank-mix of indaziflam 120 g/ha + tebuthiuron 900 g/ha or sulfentrazone 750 g/ha or diclosulam 110 g/ha was the safest option for managing *Rottboellia exaltata* and *Ipomoea quamoclit* in plant sugarcane (de Castro *et al.* 2024).

At 60 DAA, significantly lower biomass and higher control efficiency of grass weeds were observed with saflufenacil + dimethenamid-P at 835 g/ha as compared to its lower doses and other standard herbicides (**Table 3**). Ready-mix of saflufenacil + dimethenamid-P at 835 g/ha recorded 63.9% in first year and 61.9% in second year higher control of grasses weed biomass as compared to untreated control. There was lower biomass of broad-leaved weeds and sedges in plots treated with of 2,4-D dimethyl amine salt at 3500 g/ha and recorded 84.6% and 81.4% higher control of broad-

Table 2. Effect of weed management treatments on weed density (no./m^2) at 60 DAA in sugarcane

Treatment	*Echinochloa colona*		*Eleusine indica*		*Dactyloctenium aegyptium*		*Digitaria sanguinalis*		*Acrachne racemosa*		*Cyperus rotundus*		*Ipomoea nil*		*Trianthema portulacastrum*	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Saflufenacil +	2.89	2.97	3.31	3.41	3.55	3.76	3.21	3.31	3.61	3.75	5.94	5.99	3.74	3.91	4.43	4.56
dimethenamid-P 501 g/ha	(7)	(8)	(7)	(11)	(12)	(13)	(9)	(10)	(12)	(13)	(34)	(35)	(13)	(14)	(19)	(20)
Saflufenacil +	2.64	2.68	2.83	2.94	3.31	3.33	2.86	2.91	3.00	3.17	5.48	5.55	3.31	3.41	4.04	4.04
dimethenamid-P 668 g/ha	(6)	(7)	(7)	(8)	(10)	(10)	(7)	(8)	(8)	(9)	(29)	(30)	(10)	(11)	(15)	(15)
Saflufenacil +	2.45	2.53	2.65	2.76	3.05	3.18	2.51	2.64	3.00	3.05	5.20	5.31	3.11	3.24	2.94	3.01
dimethenamid-P 835 g/ha	(5)	(5)	(6)	(7)	(8)	(9)	(5)	(6)	(8)	(8)	(26)	(27)	(9)	(10)	(8)	(8)
Saflufenacil 70 g/ha	2.89	2.97	2.89	3.00	3.51	3.62	3.82	4.01	3.00	3.17	6.30	6.38	3.16	3.31	2.14	2.40
	(7)	(8)	(7)	(8)	(11)	(12)	(14)	(15)	(8)	(9)	(39)	(40)	(9)	(10)	(4)	(5)
Dimethenamid-P 600 g/ha	2.58	2.64	2.71	2.82	3.21	3.33	2.71	2.76	2.89	3.02	6.14	6.22	3.46	3.60	4.68	4.64
	(6)	(6)	(6)	(7)	(9)	(10)	(6)	(7)	(7)	(8)	(37)	(38)	(11)	(12)	(21)	(21)
Metribuzin 525 g/ha	2.89	2.92	2.77	2.88	3.11	3.28	2.77	2.84	3.16	3.27	6.08	6.15	2.44	2.70	2.08	2.23
	(7)	(8)	(7)	(7)	(9)	(10)	(7)	(7)	(9)	(10)	(36)	(37)	(5)	(6)	(3)	(4)
2,4-D dimethyl amine salt	3.74	3.84	3.41	3.50	4.47	4.37	4.35	4.34	3.60	3.65	5.13	5.26	1.14	1.50	1.00	1.21
3500 g/ha	(13)	(14)	(11)	(11)	(19)	(18)	(18)	(18)	(12)	(12)	(25)	(27)	(0)	(1)	(0)	(1)
Weed free check	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Untreated control	4.00	4.09	3.55	3.64	4.86	4.88	4.51	4.58	3.70	3.82	6.38	6.46	3.96	4.11	4.86	4.94
	(15)	(16)	(12)	(12)	(23)	(23)	(19)	(20)	(13)	(14)	(40)	(41)	(15)	(16)	(23)	(23)
LSD (p=0.05)	0.19	0.15	0.21	0.23	0.28	0.29	0.35	0.27	0.23	0.18	0.21	0.17	0.26	0.30	0.34	0.23

*Data is subjected to square root transformation ($\sqrt{x+1}$). Figures in parentheses are means of original values in round figures; DAA = days after herbicide application leaved weeds and 55.9% and 54.8% sedges in first and second year, respectively over untreated control. Among all the herbicidal treatments, application of 2,4-D dimethyl amine salt at 3500 g/ha also registered significantly higher weed control efficiency of broad-leaved weeds (98.2% in first year and 96.7% in second year) and sedges (80.3% in first year and 79.3% in second year). Moreover, ready-mix application of saflufenacil plus dimethenamid-P at 835 g/ha resulted in statistically similar sedges weed biomass and weed control efficiency with 2,4-D dimethyl amine salt at 3500 g/ha during both the years of study.

The new molecule, saflufenacil, a selective herbicide belongs to the pyrimidinedione (uracil) group, and can be used both pre- and post-emergence in certain crops. Once applied and absorbed by plants, saflufenacil primarily translocate through the xylem, with limited movement through the phloem (BASF 2025). This herbicide works by inhibiting the enzyme protoporphyrinogen oxidase (PPO), which is involved in chlorophyll and cytochrome synthesis, leading to plant death. It increases the production of highly reactive singlet oxygen, which causes lipid peroxidation, necrosis and subsequent cell death. Dimethenamid, a chloroacetamide herbicide, inhibiting the synthesis of very long-chain fatty acids helps to prevent the weed growth when applied as pre-emergent herbicide. As a broad-spectrum herbicide, it is used on crops such as corn, soybean, sugarcane and peanut, effectively controlling both grass and broad-leaf weeds (Aulakh 2023). Dimethenamid-P is known for its low toxicity and environmental safety, posing no carcinogenic risks. Its ability to be effective at half the dosage of its racemic mixture further highlights its efficiency.

Application of dimethenamid-P registered effective control of grasses by inhibiting very long chain fatty acids while saflufenacil provided good control of broad-leaved weeds by inhibiting protoporphyrinogen oxidase that provides both contact and soil residual control of broad-leaved weeds (Moran *et al.* 2011). Effective weed control with the pre-emergence application of ready-mix of saflufenacil plus dimethenamid-P was also reported by Odero *et al.* (2014). Moran *et al.* (2011) observed application of saflufenacil plus dimethenamid-P resulted in 95% total weed biomass reduction in maize. In our study, application of ready-mix of saflufenacil plus dimethenamid-P at 835 g/ha was effective on weeds at 60 DAA but weed biomass in this combination was significantly more than weed free that indicated that there is a need of post-emergence weed management option (at 60 days old crop) in sugarcane. Sugarcane, being a long duration crop and heavy infestation of annuals and perennials necessitate the post-emergence cultural and/or chemical weed management option to achieve satisfactory weed control after this pre-emergence herbicide application. Singh *et al.* (2008) reported that pre-emergence application of metribuzin at 0.080 kg/ha or ametryn at 2.0 kg/ha with two hoeings done at 60 and 90 days after planting were most effective against most of the weeds.

Table 3. Effect of weed management treatments on weed biomass and weed control efficiency at 60 DAA in sugarcane

Treatment	Weed biomass (g/m^2)						Weed control efficiency (%)					
	Grass weeds		Broad-leaved weeds		Sedges		Grass weeds		Broad-leaved weeds		Sedges	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Saflufenacil + dimethenamid-P 501 g/ha	13.96 (194)	13.71 (187)	9.78 (95)	10.06 (100)	14.16 (200)	14.26 (203)	62.6	58.2	37.1	37.3	19.0	18.8
Saflufenacil + dimethenamid-P 668 g/ha	11.23 (125)	11.02 (121)	8.99 (80)	9.28 (86)	11.18 (125)	11.31 (128)	75.9	73.1	47.1	46.4	49.9	49.3
Saflufenacil + dimethenamid-P 835 g/ha	8.26 (67)	8.08 (65)	6.70 (44)	7.13 (50)	8.23 (68)	8.40 (71)	87.2	85.6	70.2	68.8	72.9	72.0
Saflufenacil 70 g/ha	16.56 (273)	15.96 (254)	5.58 (30)	6.04 (36)	14.75 (217)	14.85 (220)	47.6	43.3	79.9	77.5	12.0	11.9
Dimethenamid-P 600 g/ha	10.82 (116)	10.57 (111)	10.56 (111)	10.82 (116)	13.82 (190)	13.92 (193)	77.7	75.3	26.4	27.2	21.9	21.7
Metribuzin 525 g/ha	14.18 (200)	13.74 (188)	3.94 (15)	4.60 (20)	14.42 (208)	14.53 (211)	61.4	58.0	90.2	87.3	16.3	16.0
2,4-D dimethyl amine salt 3500 g/ha	19.82 (392)	18.52 (342)	1.90 (3)	2.36 (5)	6.94 (48)	7.17 (51)	24.5	23.5	98.2	96.7	80.3	79.3
Weed free check	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	100.0	100.0	100.0	100.0	100.0	100.0
Untreated control	22.89 (523)	21.19 (448)	12.31 (151)	12.69 (160)	15.75 (148)	15.85 (251)	-	-	-	-	-	-
LSD (p=0.05)	1.00	0.58	0.82	0.96	1.38	1.36	6.8	3.5	7.8	8.9	13.9	13.8

*Data is subjected to square root transformation ($\sqrt{x+1}$). Figures in parentheses are means of original values in round figures. Weed control efficiency was calculated based on weed biomass; DAA = days after herbicide application

Effect on sugarcane growth, yield attributes and cane yield

All herbicidal treatments registered significant impact on the sugarcane's yield attributes and yield but there was non-significant difference in all weed control treatments for plant height of sugarcane at 60 DAA during both the years of study. Saflufenacil + dimethenamid at 501 to 835 g/ha and weed free check treatments recorded statistically similar number of tillers at 60 DAA and was significantly higher over other weed control treatments and untreated control. The cane length of sugarcane did not differ significantly with different treatments during both the years of study. The ready-mix application of saflufenacil + dimethenamid-P at 835 g/ha recorded 20.8% and 20.9% more number of millable canes during first and second year of crop, over untreated control plot.

The highest cane yield was recorded with weed free check and the lowest cane yield were recorded with untreated control plots. The cane yield with ready-mix of saflufenacil + dimethenamid-P at 835 g/ha was statistically similar with weed free check but was significantly higher than other herbicide treatments and untreated control plots. Ready-mix of saflufenacil + dimethenamid-P at 835 g/ha improved the cane yield 62.3 to 65.2% over the untreated control plots, and led to a significant increase in cane yield by 65.2% and 62.3% in first and second year over untreated control plots (**Table 4**). This yield improvement is attributed to the enhanced weed control efficiency and improved yield attributes with herbicidal treatment. By effectively suppressing weed growth at early stages, pre-emergence herbicides reduced competition for essential resources such as moisture, space, light and nutrients, thereby promoting better crop growth and higher productivity. Pre-emergence application of saflufenacil plus dimethenamid-P has the potential to provide effective weed control (>90%) at 42 days after treatment and produced satisfactory corn yield (Odero *et al.* 2014). Further, integrating pre-emergence application of metribuzin 1.25 kg/ha with post-emergence application of 2,4-D 1.0 kg/ha in sugarcane exhibited 65.3% weed control efficiency which was comparable with three hand hoeing at 30, 60 and 90 DAP (Singh and Kumar 2013).

Table 4. Effect of weed management treatments on growth, yield attributes and yield of sugarcane

Treatment	Plant height at 60 DAA (cm)		Tillers at 60 DAA (no./m^2)		Cane length (m)		Millable canes ($x10^3$/ha)		Cane yield (t/ha)	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Saflufenacil + dimethenamid-P 501 g/ha	55.8	55.3	14.7	15.6	3.4	3.5	129.4	129.2	58.9	57.9
Saflufenacil + dimethenamid-P 668 g/ha	56.2	55.0	14.9	15.8	3.4	3.5	133.6	134.1	66.4	65.8
Saflufenacil + dimethenamid-P 835 g/ha	56.5	56.3	15.6	15.9	3.4	3.5	137.9	137.7	76.8	79.2
Saflufenacil 70 g/ha	53.9	53.7	12.7	12.7	3.4	3.4	115.3	115.0	57.1	54.2
Dimethenamid-P 600 g/ha	54.6	53.9	12.9	12.8	3.4	3.5	127.1	126.8	66.6	66.3
Metribuzin 525 g/ha	55.0	54.7	12.6	12.2	3.4	3.5	125.3	125.1	65.7	63.4
2,4-D dimethyl amine salt 3500 g/ha	55.2	56.4	12.7	12.4	3.4	3.4	125.0	124.8	60.1	62.5
Weed free check	56.0	56.1	14.8	15.2	3.5	3.6	156.2	155.9	81.1	84.8
Untreated control	54.6	54.1	12.3	12.0	3.1	3.2	114.1	113.9	46.5	48.8
LSD (p=0.05)	NS	NS	1.2	1.6	NS	NS	13.1	12.7	10.4	9.7

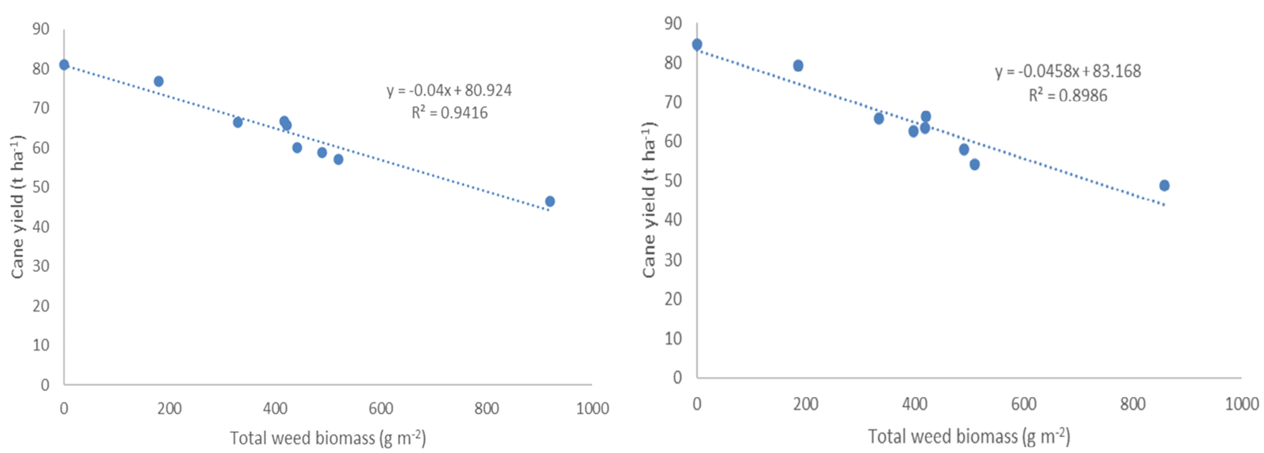

Figure 1. The relationship of cane yield with total weed biomass at 60 DAA during 2018 and 2019

The linear regression analysis illustrates the relationship between total weed biomass and sugarcane yield (**Figure 1**). A strong negative linear correlation (r= -0.97 and -0.95 for 2018 and 2019, respectively) of weed biomass at 60 DAA with cane yield was observed. As total weed biomass increased, sugarcane yield decreased correspondingly. The R^2 values of 0.9416 and 0.8986 indicates that weed biomass accounted for 94% and 90% of the yield variation during 2018 and 2019, respectively. The findings highlighted a significant influence of weed control treatments on both weed biomass and cane yield.

Based on the findings of two-year study, it was concluded that saflufenacil + dimethenamid-P at 835 g/ha as PE effectively controlled wide range of grasses, broad-leaved weeds and sedges, and resulted in cane yield statistically comparable to weed free check. However, it is suggested that for a long duration crop like sugarcane, solo application of pre-emergent herbicide is often inadequate and sequential application of pre- and post-emergence herbicides are crucial for effective weed management to produce more millable canes and cane yield.

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RESEARCH ARTICLE

Mikania management in coffee plantation with pre- and post-emergent herbicide combinations

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ABSTRACT

Potential yield of coffee in Northeast India is adversely affected by *Mikania micrantha* Kunth infestations. The study, conducted at Diphu, Assam during 2016 and 2017, was aimed to managing *Mikania micrantha* in coffee plantations through hastening the seed germination by soil application of gibberellic acid and killing the germinated seedlings by pre- and post-emergent herbicide application. Gibberellic acid 500 ppm significantly increased the *Mikania micrantha* seed germination, than 250 ppm, and control without any effect on the growth and yield of coffee. Oxyfluorfen 0.29 kg/ha followed by (*fb*) glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha and oxyfluorfen 0.29 kg/ha *fb* glyphosate (0.99 kg/ha) resulted in successful management of *M. micrantha* and significantly increased the vegetative growth and yield of coffee as compared to the weedy check. Highest net return and B:C ratio during 2016-17 and 2017-18 were observed with oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha. Next best treatment was oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha. At present, 2,4-D usage is not recommended for coffee. Therefore, oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha can be recommended for control of *Mikania micrantha* in coffee plantations.

Keywords: Coffee, 2,4-D, Economics, Glyphosate, *Mikania micrantha* Kunth, Oxyfluorfen, Weed management

INTRODUCTION

Coffee occupies an area of 479669 ha in India with an annual production of 352000 MT, accounting for 3.41% of world coffee production and 5.11% of world exports (Anonymous 2023). The coffee industry provides employment for over one million Indians earning US$ 1.28 billion as foreign exchange.

In India, coffee is grown under the canopy of forest and fruit trees and conserve bio-diversity of the coffee growing regions. In the hilly areas of Northeast India, shifting cultivation is widely practiced (0.76 million ha) by the indigenous people (Choudhury *et al*. 2016) which has rendered the land unproductive and caused environmental degradation. Coffee cultivation was introduced in this region during 1960s with the aim for stopping shifting cultivation, preservation of the fragile ecosystem and for socio-economic upliftment of the local people. (Bora and Barman 2015). At present 5647 ha area is under coffee in North East India and an additional area of 38353 ha has been identified as potential sites for coffee cultivation. Despite its great potential, the productivity of coffee is restricted to 101 kg/ha in this region (Langthasa and Bora 2013) compared to the national average of 814 kg/ha, Incidence of diseases, insect pests, and above all competitive weeds are the main reasons for the low productivity of coffee in Northeast India. Amongst these, *Mikania micrantha* Kunth is the most problematic weed, posing serious threat to successful coffee cultivation with its ability to grow over the coffee plants covering the crown and adversely affecting photosynthesis (Bora *et al*. 2023).

Mikania micrantha belonging to the family Asteraceae is an invasive perennial vine native to Central and South America (Barreto and Evans 1995). It is believed to have been introduced in Northeast India as a ground cover during World War II (Ni *et al*. 2007). Subsequently, the weed has spread to all the coffee-growing areas of the region. The Mikania plant can grow up to 47 cm in a week (Zhang *et al*. 2004) and possesses tremendous smothering ability

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by covering the underneath plants thereby hindering photosynthesis (Li *et al*. 2007). This weed is well adapted to the subtropical warm temperate climate of North-East India. It has the capacity of producing around 0.17 million seeds/ m^2 (Kuo 2003). These tiny seeds (0.087±0.016 g/1000 seed) are wind-dispersed over long distances, remain in the soil within 1.5 to 1.75 cm depth (Yang *et al*. 2005) and are known to persist for about 7 years in the soil seed bank (Brooks *et al*. 2008). In North-East India, seed dispersal of the weed takes place from January to March. Seed germination and emergence of vines occur whenever there is sufficient moisture in the soil at any time up to the year-end (December). The germination of *M. micrantha* seeds was reported to get enhanced with different concentrations of gibberellic acid (GA) (Nyamongo *et al*. 2009).

Due to high *M. micrantha* infestation, the coffee plantations of Northeast India suffered up to 80% yield loss (Bora, 2018). As a result, some of the coffee plantations were abandoned as the farmers could not afford the monetary loss. Control of *M. Micrantha* with pre- and post-emergence herbicides such as oxyfluorfen, glyphosate, 2,4-dichlorophenoxyacetic acid (2,4-D), diuron, paraquat, dalapon, and triclopyr are widely used in plantations. Wibowo *et al*. (2007) recommended application of glyphosate in rubber. In coffee plantations of India, glyphosate and paraquat are recommended herbicides for weed control. However, a single application of herbicide was not found to be effective against *M. micrantha* because germination of seeds and emergence take place at different times of the year depending on rainfall and soil moisture. Even though many herbicides were found suitable against *M. micrantha*, it may be a challenge to use them in the coffee plantations as coffee plant was sensitive to many of the herbicides. Post-emergence application of sulfentrazone, oxyfluorfen and lactofen imposed high injury to the young coffee plants (Ronsi and Silva 2003). Further, during the application, the drift of glyphosate impaired the growth of young coffee plants. A drift of 2,4-D caused fruit shedding in both lower and upper branches of coffee. In bearing coffee plantations, the chances of herbicide drift to coffee plants are higher as the primary and secondary branches of coffee plants spread horizontally. Hence, a detailed studies on the efficacy of herbicides in the management of *M. micrantha* in coffee plantation and their effect on the growth and yield of coffee are required before recommending the herbicides to the farmers. However, no systematic study on these aspects has been done in Northeast India.

The aim of the present study was to develop an effective management strategy for the weed *M. micrantha* and to reduce the coffee yield loss. Accordingly, a study was conducted to assess the feasibility of enhancing the germination of *M. micrantha* seeds with different concentrations of gibberellic acid (GA) and to control *M. micrantha* using selected herbicides and their combinations.

MATERIALS AND METHODS

The field study was carried out during 2016 and 2017 in coffee plantation at the Regional Coffee Research Station (25°92'N, 93°44'E, 170 m ASL) situated at Diphu, Assam, India. During the two years experimental period, the weekly mean maximum temperature ranged from 20.7° C to 35.3° C whereas weekly mean minimum temperature ranged from 6.2° C to 28.3° C. The weekly average relative humidity ranged from 85 to 96 percent during the morning hours, while in the evening hours it ranged from 47 to 82.9 percent. The total rainfall received during 2016 and 2017 were 907.2 mm and 756.2 mm respectively. The soil of the experimental site was loamy sand with a pH value of 5.06, medium in organic carbon, available nitrogen, available potassium and low in available phosphorus.

Robusta coffee (*Coffea canephora*) Selection 3R was used for the study. The coffee plants were 10 years old, planted under different shade trees (*Albizia* spp., *Acacia* spp., *Artocarpus heterophyllus* etc.) in the square system of planting at a spacing of 2.7 m x 2.7 m.

Density of *M. micrantha* in the experimental field was recorded by using quadrat (0.5m x 0.5m) at 40, 80, 120 and 160 days after GA application (DAGA) and expressed as leaf number, leaf area and dry weight in gram per square metre.

Five bearing coffee plants were randomly selected from each plot to record vegetative characters, yield attributing characters and fruit yield. The leaf area was estimated from the formula prescribed by Awatramani and Gopalakrishna (1965) and was expressed as cm^2/ plant

$$Y= K \times L \times B$$

Where, Y= estimated area (cm^2), L= leaf length (cm), B= maximum width (cm) and K = 0.65 (for robusta coffee).

The field experiment was laid out in factorial randomized block design with three replications of nine treatments consisting of three concentrations of GA, *viz*. 0 ppm, 250 ppm, and 500 ppm and herbicide application in three combinations, *viz*. oxyfluorfen

(0.29kg/ ha) followed by (*fb*) glyphosate 0.99 kg/ha, oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha (applied separately) and weedy check. Each experimental block consisted of 25 coffee plants. GA powder (90%) w/w was diluted to 250 ppm and 500 ppm with distilled water and sprayed on the soil surface using knapsack hand sprayer with flood jet nozzle after removal of all the weeds from the plot ensuring that the soil is moistened at least to a depth of 2 cm. Pre-emergence application (PE) of oxyfluorfen 0.29 kg/ha was done on the soil surface with a knapsack sprayer and flood jet nozzle. Post-emergence application (PoE) of glyphosate 0.99 kg/ha and 2, 4-D Sodium salt 0.73 kg/ha was done targeting the foliage of *M. micrantha* in the field using a similar sprayer and nozzle. The herbicides were applied when 80% of *M. micrantha* plants attained 5-10 cm length.

Factorial randomized complete block design (RCBD) was used to analyse the response of the different treatments as well as their combinations on various parameters of the study. The statistical analysis was performed using International Business Machine (IBM) Statistical Package for Social Sciences (SPSS) version 25.0 and the graphs were prepared using Microsoft Excel 2019.

RESULTS AND DISCUSSION

In both the years of experimentation, under field conditions, the application of GA 500 ppm recorded significantly higher *M. micrantha* leaf number, leaf area, density and dry weight at 40 DAGA compared to GA 250 ppm and the check with no GA application (**Table 1** and **3**). The interaction effects of GA concentration and herbicide treatments were observed on leaf number, leaf area, density and dry weight of *M. micrantha* at 40 DAGA (**Table 2** and **4**). Significantly higher values of the vegetative parameters were recorded with the application of GA 500 ppm compared to GA 250 ppm and no GA application which might be due to the enhanced germination of *M. micrantha* seeds present in the soil as a result of GA application at higher concentrations. Along with *M. micrantha* other weed seeds i.e. *Oplismenus compositus, Sporobolus* sp. and *Cleome rutidosperma* also germinated due to GA application and were destroyed with the herbicide treatment.

In this study, oxyfluorfen 0.29 kg/ha was applied at 20 DAGA, and *M. micrantha* emergence was recorded at 40 DAGA which implied that complete eradication of the weed was not possible although the pre-emergent application of oxyfluorfen 0.29 kg/ha partially controlled the weed (**Table 1** and **3**) A similar observation was recorded by Ghosh and Ramakrishnan (1981) in a study to control *M. micrantha* in tea.

At 80, 120, and 160 DAGA, no significant difference in *M. micrantha* leaf number, leaf area and dry weight at different GA concentrations were observed (**Table 1** and **3**). Significantly higher *M. micrantha* leaf number and leaf area and dry weight were recorded in weedy plots at 40, 80, 120, and 160 DAGA as compared to other treatments (**Table 1** and **3**). Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha and oxyfluorfen 0.29 kg/ha, followed by glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha had successfully controlled *M. micrantha* (**Table 1** and **3**). Sellers *et al.* (2014) reported that the glyphosate caused 70% or greater control of *M. micrantha* due to its high efficacy in controlling the weed. Better result of glyphosate on controlling *M. micrantha* was also reported by Shen *et al.* (2013). The combination of glyphosate + 2, 4-D was reported to be effective for controlling *M. micrantha* in *Shorea selanica* plantations (Wibowo and Nazif 2007).

Table 1. Effect of GA concentration and herbicides treatments on *Mikania micrantha* leaf number and leaf area

Treatment	*Mikania micrantha* leaf number (no./ m^2)								*Mikania micrantha* leaf area (cm^2/ m^2)							
	40 DAGA		80 DAGA		120 DAGA		160 DAGA		40 DAGA		80 DAGA		120 DAGA		160 DAGA	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
GA concentration																
Without GA	17.6	16.2	30.9	28.9	23.8	6.0	20.0	22.2	215.9	197.7	393.6	339.7	302.0	322.2	250.1	284.1
GA 250 ppm	28.7	27.3	30.7	30.4	24.0	27.6	21.8	23.8	362.7	324.3	383.8	375.1	304.8	341.1	271.4	203.1
GA 500 ppm	36.7	38.4	32.0	32.0	27.6	28.2	22.2	24.0	452.6	457.7	397.9	374.8	349.9	349.1	276.7	306.5
LSD (p=0.05)	4.4	4.3	NS	NS	NS	NS	NS	NS	48.8	47.3	NS	NS	NS	NS	NS	NS
Herbicide																
Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha	21.1	15.8	0.0	0.0	0.0	0.0	0.0	0.0	272.0	188.2	0.0	0.0	0.0	0.0	0.0	0.0
Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha) + 2,4-D 0.73 kg/ha	21.6	16.7	0.0	0.0	0.0	0.0	0.0	0.0	268.8	201.8	0.0	0.0	0.0	0.0	0.0	0.0
Weedy	40.2	49.6	93.6	91.3	75.3	81.8	64.0	70.0	490.4	589.5	1175.2	1088.6	956.8	1012.4	798.2	893.7
LSD (p=0.05)	4.4	4.3	4.6	4.6	3.9	3.4	3.1	3.5	48.8	47.3	46.0	65.9	48.8	42.2	38.2	44.5
Interaction (HxG)	7.6	7.5	NS	NS	NS	NS	NS	NS	84.5	82.0	NS	NS	NS	NS	NS	NS
CV (%)	15.9	15.8	14.7	15.7	15.6	12.5	14.7	15.2	14.2	14.5	11.7	15.0	15.3	12.5	14.3	15.0

fb= followed by; S- significant: NS= Not significant

Effect on vegetative characters, yield attributing characters, and yield of coffee

In mature coffee, the vegetative and yield attributing characters like the length of the primary branch, leaf number, leaf area, number of bearing nodes in the primary branch, number of fruits per node as well as fruit and clean coffee yield were statistically at par among GA treatments in both the years of the study (**Table 5**). Amongst tested herbicide treatments, oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha and oxyfluorfen 0.29 kg/ ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha caused a significant increase in vegetative characters (length of the primary branch, leaf number, leaf area), yield attributing characters (number of bearing nodes in the primary branch, number of fruits per node) and fruit yield. In comparison to weedy control, the coffee fruit yield (kg/plant) was 175% and 184 % higher in 2016 and 223% and 292% per plant in 2017 while the clean coffee yield was higher by 174% and 183% in

Table 2. Effect of GA concentration and herbicide treatments interaction on *Mikania micrantha* leaf number and leaf area at 40 days after GA application

GA concentration	*Mikania micrantha* leaf number (no./m^2) herbicides						*Mikania micrantha* leaf area (cm^2/m^2) herbicides					
	Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha		Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha) + 2,4-D 0.73 kg/ha		Weedy		Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha		Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha		Weedy	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Without GA	8.00	7.33	6.67	8.00	38.00	33.33	97.10	89.03	82.87	97.65	467.87	406.35
GA 250 ppm	23.33	10.00	22.67	14.67	40.00	57.33	324.53	119.93	281.25	179.79	482.25	673.11
GA 500 ppm	32.00	30.00	35.33	27.33	42.67	58.00	394.36	355.73	442.27	328.12	521.17	689.17
LSD (p=0.05)	7.60	7.50	7.60	7.50	7.60	7.50	84.47	82.01	84.47	82.01	48.77	82.01
CV(%)	15.88	15.85	15.88	15.85	15.88	15.85	14.20	14.51	14.20	14.51	14.20	14.51

Table 3. Effect of GA concentration and herbicide on *Mikania micrantha* density (no./ m^2) and biomass (g/ m^2)

Factors	*Mikania micrantha* density								*Mikania micrantha* biomass							
	40 DAGA		80 DAGA		120 DAGA		160 DAGA		40 DAGA		80 DAGA		120 DAGA		160 DAGA	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
GA concentration																
Without GA	1.09	0.99	1.34	1.34	1.28	1.28	1.18	1.23	0.82	0.78	1.11	1.10	1.35	1.35	1.55	1.63
GA 250 ppm	1.23	1.15	1.36	1.36	1.29	1.30	1.20	1.25	0.85	0.82	1.13	1.12	1.37	1.37	1.58	1.68
GA 500 ppm	1.38	1.30	1.38	1.36	1.32	1.30	1.20	1.25	0.91	0.89	1.11	1.13	1.39	1.37	1.58	1.68
LSD (p=0.05)	0.12	0.13	NS	NS	NS	NS	NS	NS	0.04	0.05	NS	NS	NS	NS	NS	NS
Herbicides																
Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Weedy	2.29	2.03	2.67	2.65	2.47	2.46	2.17	2.32	1.16	1.08	1.93	1.94	2.69	2.68	3.29	3.58
LSD (p=0.05)	0.12	0.13	0.13	0.09	0.16	0.10	0.10	0.10	0.04	0.05	0.10	0.10	0.17	0.10	0.16	0.20
Interaction (HxG)	S	S	NS	NS	NS	NS	NS	NS	S	S	NS	NS	NS	NS	NS	NS
CV(%)	9.97	11.37	9.32	6.90	12.29	7.44	8.14	8.36	4.55	6.02	8.54	8.97	12.59	7.67	10.07	11.77

fb= followed by; S- significant: NS= Not significant

Table 4. Effect of GA concentration and herbicides interaction on *Mikania micrantha* density and biomass at 40 days after GA application

GA concentration	*Mikania micrantha* density (no./m^2)						*Mikania micrantha* biomass (g/m^2)					
	Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha		Oxyfluorfen (0.29 kg/ha) *fb* glyphosate 0.99 kg/ha + 2,4-D (0.73 kg/ha)		Weedy		Oxyfluorfen (0.29 kg/ha) *fb* glyphosate (0.99 kg/ha)		Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha		Weedy	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Without GA	0.71	0.71	0.71	0.71	1.86	1.56	0.71	0.71	0.71	0.71	1.04	0.93
GA 250 ppm	0.71	0.71	0.71	0.71	2.27	2.04	0.71	0.71	0.71	0.71	1.15	1.06
GA 500 ppm	0.71	0.71	0.71	0.71	2.73	2.48	0.71	0.71	0.71	0.71	1.30	1.24
LSD (p=0.05)	0.21	0.23					0.07	0.09				
CV (%)	9.97	11.37					4.55	6.02				

2016 and 221% and 234% per ha with oxyfluorfen (0.29 kg/ha) *fb* glyphosate 0.99 kg/ha and oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2,4-D 0.73 kg/ha, respectively.

Both the herbicide treatments were at par in both the years regarding the vegetative and reproductive characters of coffee. The effect of the GA application was visible up to 40 DAGA only and thereafter it disappeared. This might be the reason that no effect of soil-applied GA was observed on vegetative characters, reproductive characters, and yield of coffee plants.

In the weedy control plots, *M. micrantha* vines completely covered the canopy of the coffee plants and thus reduced leaf number and, leaf area leading to reduced photosynthetic ability which in turn adversely affected number of bearing nodes and number of fruits per node resulting in reduced fruit and clean coffee yield. Further, *M. micrantha* covering increased relative humidity and created a barrier for sunlight and wind which might have changed the microclimate to more favourable proportions for black rot fungus (*Koleroga noxia* Donk) to proliferate in *M. micrantha* infested coffee plants. The saturated atmosphere with 95-100% relative humidity, thick shade, and absence of sunlight and wind are conducive to black rot disease in coffee which manifests as blackening and rotting of infected leaves, developing fruits, and young twigs. The incidence of black rot in the weedy (control) plots of mature coffee was 22.66% (2016-17) and 20% (2017-18) during the hot humid monsoon months of June to August in both years. The disease induced significantly shorter primary branches, fewer leaves, and reduced leaf area of the coffee plants. Measurement of the incidence of black rot disease (per cent) was done based on the number of plants affected according to Daivasikamani *et al.* (2016) in the weedy plots where the disease was observed due the shift in the microclimate of the weedy plots to favourable proportions for the disease. Subsequently, a significantly lesser number of bearing nodes in

Table 5. Vegetative characters, yield attributing characters and yield of coffee as influenced by GA concentration and herbicides

Factors	Vegetative characters						Yield attributing characters						Yield	
	Length of primary branch (cm)		Leaf no. (no./ plant)		Leaf area (cm^2 /plant)		No. of bearing node per primary branch		Fruits per node (no.)		Fruit yield (kg/plant)		Clean coffee yield (kg/ha)	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
GA concentration														
Without GA	145.38	160.64	1024	1064	142216	147698	13.36	14.27	19.31	17.47	1.82	1.88	483.46	500.67
GA 250 ppm	141.16	157.23	1144	1158	158787	160730	13.53	14.70	19.38	16.89	1.76	1.85	466.63	491.81
GA 500 ppm	148.48	164.81	1167	1192	162072	165495	13.53	14.73	19.13	17.18	1.77	1.89	469.58	502.89
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Herbicides														
Oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha	154.79	170.18	1245	1290	172867	179175	16.18	18.14	22.84	22.36	2.23	2.39	592.73	635.38
Oxyfluorfen 0.29 kg/ha *fb* glyphosate (0.99 kg/ha) + 2,4-D 0.73 kg/ha	152.43	168.94	1287	1362	178681	189091	16.37	18.23	23.60	23.20	2.30	2.9	611.04	661.96
Weedy	127.79	143.57	803	761	111525	105657	7.88	7.33	11.38	5.98	0.81	0.74	215.89	198.02
LSD (p=0.05)	16.55	16.75	147	129	20426	18024	2.55	2.81	2.41	2.26	0.31	0.37	82.93	97.13
Interaction (HxG)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	11.42	10.42	13.2	11.4	13.2	11.4	18.85	19.29	12.51	13.19	17.54	19.68	17.54	19.50

fb= followed by; S- significant: NS= Not significant

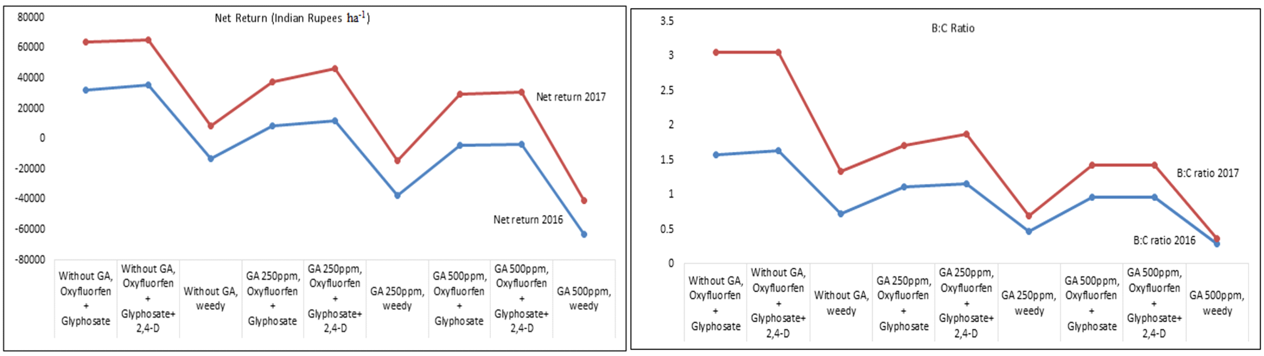

Figure 1. Economic evaluation (B:C ratio, Benefit cost ratio) of different treatments in coffee

primary branches (52% in 2016-17 and 59.8% in 2017-18) of the plants in control plots were recorded coupled with mature fruit drop of 12.22% and 10.30% inflicted yield loss of 64.66% and 70.08% in 2016-17 and 2017-18, respectively. No such yield loss was recorded in Mikania free plots. Anand *et al.* (2014) reported that during the monsoon season, prolonged soil saturation induced high levels of mature fruit drop in coffee to an extent of 20–30%. Thus, fruit drop combined with the incidence of black rot could be the major reasons for significantly fewer fruits per node of coffee plants in control plots. Better weed control due to herbicide treatments might have favoured higher leaf number, leaf area, better environment for photosynthesis, leading to more number of bearing nodes, fruits per node which ultimately produced more coffee fruits per plant.

Economics

The highest net return and highest benefit-cost (B: C) ratio (**Figure 1**) were recorded with oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha + 2, 4-D 0.73 kg/ha. This was followed by the treatments combining oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha. The lowest net return was realized in 2016-17 and 2017-18 with the combination of GA 500 ppm and weedy.

It is concluded that effective management of *M. micrantha* in the coffee plantations of North East India can be achieved by the application of either oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha) + 2,4-D (0.73 kg/ha) or oxyfluorfen 0.29 kg/ha *fb* glyphosate 0.99 kg/ha as observed by Bora et al. (2019). As 2,4-D is not permitted to be used in India, application of oxyfluorfen 0.29 kg/ha followed by glyphosate 0.99 kg/ha can be recommended for management of *M. micrantha* in coffee plantations.

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RESEARCH ARTICLE

Use of silver nanoparticles biosynthesized from leaf extracts of three allelopathic weeds for the management of water hyacinth (*Pontederia crassipes* Mart.)

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ABSTRACT

Silver nanoparticles (AgNPs) were biosynthesized from the leaf extracts of *Lantana camara* L. (*Lc*), *Parthenium hysterophorus* L. (*Ph*) and *Coleus amboinicus* Lour. (*Ca*), which possess allelopathic effects on the aquatic weed 'water hyacinth' (*Pontederia crassipes* Mart.). Their herbicidal efficacy was physically characterized and assessed. The absorption maxima of the synthesized nanoparticles (NPs) were typical to those of AgNPs according to spectroscopy, and they possessed a face-centred cubic structure according to X-ray diffraction. Among the three biosynthesized NPs, *Ph*-AgNPs exhibited better stability, with a zeta potential of -32.7 mV, and dynamic light scattering at a size range of 213 nm. There was a significant difference in necrosis on water hyacinth leaves after spraying with a 1 ppm *Ph*-AgNP suspension as compared to that on leaves sprayed with *Lc*-AgNP and *Ca*-AgNP suspensions with the same concentration. The water hyacinth plants sprayed with 10 ppm *Ph*-AgNPs had the lowest number of leaves, leaf length, leaf width, bud diameter, root length and plant height at 15 days after treatment (DAT). *Ph*-AgNPs at a concentration of 10 ppm significantly decreased the total chlorophyll content, carbohydrate content, protein content, photosynthetic rate and stomatal conductance in the leaf tissue of water hyacinth at 5 DAT. The phenol content and superoxide dismutase (SOD) activity in water hyacinth plants significantly increased in response to the application of the biosynthesized NPs. This study revealed the feasibility of utilizing a noxious weed, by exploiting its natural chemical properties, to manage by suppressing growth of another difficult-to-control noxious weed. The use of AgNPs biosynthesized from *P. hysterophorus* leaf extract effectively inhibited the growth of water hyacinth. However, accurate evaluation of AgNPs toxicity requires comprehensive, long-term studies under realistic environmental conditions to understand ecological factors interactions.

Keywords: Allelopathic potential, *Coleus amboinicus, Lantana camara, Parthenium hysterophorus,* Silver nanoparticles, Water hyacinth, Weed management

INTRODUCTION

Water hyacinth (*Pontederia crassipes* Mart.), also known as 'Bengal terror,' is a Brazilian aquatic plant introduced to India in 1896 as an ornamental plant. Currently, it is recognized as the most problematic aquatic weed globally as it invasively proliferates in water sources such as rivers, irrigation channels, and lakes. The International Union for Conservation of Nature (IUCN) considers it one of the most dangerous invasive species globally, causing substantial environmental and social risks, and involving drudgery for its removal from water bodies (Téllez *et al.* 2008). High levels of aquatic pollution from fertilizers containing nitrates, nitrites, and phosphates (eutrophication) have been linked to the rapid growth of water hyacinth. This noxious weed is predominantly found in rice fields, lakes, streams, and channels, making a sizable portion of waterbodies inaccessible, unusable, and non-navigable (Jayan and Sathyanathan 2012). Under ideal conditions, water hyacinth plants grow rapidly, and their population doubles in 10 days. Average fresh weight of water hyacinth plants is reportedly increased by 201 and 788% by the end of the first and fourth week, respectively (Prasetyo *et al.* 2021). Various control methods (*e.g.*, mechanical, chemical, and biological) are in use (Sushilkumar 2011, Swetha *et al.* 2012, Dutta *et al.* 2015), but they are ineffective against water hyacinth.

Mechanical methods are time- and labor-consuming and cost-prohibitive. Herbicide use pollutes waterbodies, causing harm to aquatic organisms. Biological control methods through the release of chevroned weevil (*Neochetina bruchi*),

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mottled weevil (*N. eichhorniae*) and water hyacinth borer (*Sameodes albiguttalis*) were found environmentally safe, cost-effective, and beneficial for aquatic animals and plants. These weevils feed on the stem tissue of water hyacinth, resulting in a loss of buoyancy for the plant, which eventually sank (Gupta and Yadav 2020). However, the life cycle of these weevils as biological predators on water hyacinth was the main limitation as it completes within 90 days.

Nanotechnology, a significant and appealing area of research, has distinctive features and broad applications in agriculture, food, and biomedicine. Various plant secondary metabolites, such as polysaccharides, proteins, polyphenols, flavonoids, terpenoids, tannins, alkaloids, amines, ketones, and aldehydes, play roles as reducing, stabilizing, and capping agents in converting metal ions to nanoparticles (NPs). Silver nanoparticles (AgNPs) have stood out among other NPs in the last two decades due to their distinctive biological, chemical, and physical properties (Meena *et al.* 2020). The physiological, chemical, and metabolic processes of plants are influenced by AgNPs, leading to alterations in growth, water absorption, nutrient uptake, transpiration, photosynthesis, and respiration. Additionally, AgNPs induce the generation of reactive oxygen species (ROS) and trigger antioxidant responses (Rani *et al.* 2016; Xu *et al.* 2025). Prolonged exposure to elevated levels of silver nanoparticles caused toxicity, mortality, bioaccumulation, and tissue damage in *Cyprinus caripo*, the common carp (Kakakhel *et al.* 2021). However, managing troublesome weeds with the use of AgNPs biosynthesized from plant extracts with herbicidal properties or allelopathic potentials is a novel attempt to explore the prospects of nanotechnological application in agriculture.

Congress grass (*Parthenium hysterophorus*) is an important weed that exhibits significant allelopathic (herbicidal) properties on the growth of water hyacinth (Pandey 2015). Likewise, common lantana (*Lantana camara*), a terrestrial plant, has been reported to have allelopathic effects on water hyacinth, and exhibit natural herbicidal potentials (Qureshi *et al.* 2019). The *Coleus* spp. dried leaf powder (25 g/l of water) was found most effective in reducing the fresh weight and chlorophyll content of *E. crassipes* and showed 100% reduction on 6 days after treatment (Gnanavel and Kathiresan 2013). Thus, eco-friendly NPs biosynthesized from the extracts of allelopathic weeds may offer the possibilities for a new range of bioherbicides. With this view, a study was conducted to assess the comparative efficacy of AgNPs biosynthesized from the leaf extracts of *Lantana camara* L. (Lc), *Parthenium hysterophorus* L. (Ph) *and Coleus amboinicus* Lour. (Ca) on the growth and development of water hyacinth.

MATERIALS AND METHODS

Collection of plant materials

Water hyacinth plants were collected from Vellayani Lake, and uniformly sized offsets of the plants were raised in earthen pots (of 30 cm diameter and 11 L capacity) filled with soil from the rice field up to 8–10-inch thickness, at the College of Agriculture, Vellayani (Kerala Agricultural University), Thiruvananthapuram, Kerala during 2022. Fresh leaves of *L. camara*, *P. hysterophorus*, and *C. amboinicus* were utilized for synthesizing AgNPs. *P. hysterophorus* leaves were collected from Coimbatore, Tamil Nadu and Varthur, Karnataka, whereas *L. camara* and *C. amboinicus* leaves were procured from the College of Agriculture, Vellayani. After washing twice in running water and double-distilled water, the midrib was removed, and the leaves were dried in the shade for 1-2 hours to remove excess moisture. The chopped and weighed leaves were then used for extraction. Aqueous leaf extracts (3%) of *L. camara*, *P. hysterophorus*, and *C. amboinicus* and the NPs biosynthesized from the extracts at 1 ppm and 10 ppm were applied to the pots by drenching at 7 days after planting, in three replications.

Biosynthesis of AgNPs

Dried leaves of *L. camara*, *P. hysterophorus* and *C. amboinicus*, each weighing 10 g, were thoroughly washed twice in distilled water. Finely chopped leaves were boiled in 100 ml of sterile distilled water in a round bottom flask for 90 minutes. Once cooled, the crude extract was filtered through Whatman No. 1 filter paper, and the resulting filtrate was utilized for the biosynthesis of AgNPs. A 1 mM solution of silver nitrate ($AgNO_3$) in double distilled water was prepared. It was then combined with leaf extract at a 1:4 ratio and left in darkness overnight at room temperature. Following incubation, a dark brown colour in the solution indicated the reduction of silver ions to AgNPs. The suspension was centrifuged at 10,000 rpm for 20 minutes. The resulting pellet was resuspended in sterile deionized water and then centrifuged again at 10,000 rpm for 20 minutes before being dried in a hot air oven at 40°C for 20 minutes, after which its dry weight was recorded. AgNPs were named as *Lc*-AgNPs, *Ph*-AgNPs, and

Ca-AgNPs, based on weed species used *viz. L. camara* (*Lc*), *P. hysterophorus* (*Ph*) and *C. amboinicus* (*Ca*), respectively.

Physical characterization of AgNPs

UV visible spectroscopy

Silver ion reduction to AgNPs in the colloidal solution was tracked by measuring absorption peaks using a UV-Vis spectrophotometer (SPECORD 210 PLUS - 223F1427) by scanning the wavelengths from 200 to 800 nm in a quartz cuvette with sterile deionized water as a reference.

Dynamic light scattering and zeta potential analysis

A Particle Size Analyser operating at a 90° scattering angle and a temperature of 25°C was used to examine the size and distribution of the produced NPs. The surface charge of the developed NPs was measured using Zeta Pals (Brookhaven, NY, USA).

Scanning electron microscopy

The water-based suspension containing AgNPs was drop-cast onto a scanning electron microscope stub using carbon tape and subsequently dried. Scanning electron microscopy (SEM) analysis was performed with a JEOL/EO JSM-6390 instrument to determine the morphology of the synthesized NPs.

X-ray diffraction analysis

The crystalline structure of the synthesized AgNPs was examined using an X-ray diffractometer (PANalytical-XPERT PRO diffractometer system) operating at 40 kV and 30 mA. Cu-K*a* radiation with a wavelength of 1.54 Å was used to capture diffraction patterns within the 2θ range from 20° to 120°. The crystallite size was calculated using Debye-Scherrer's equation: $D = 0.94\ \lambda/\beta \cos\theta$.

Treatment with biosynthesized NPs

The prepared AgNPs were added to the water in the pots to achieve final concentrations of 1 mg/L and 10 mg/L. The addition of distilled water served as a control. The treatments consisted of *L. camara* (*Lc*) aqueous extract at 3%, *Lc*-AgNPs at 1 ppm, *Lc*-AgNPs at 10 ppm, *P. hysterophorus* (*Ph*) aqueous extract at 3%, *Ph*-AgNPs at 1 ppm, *Ph*-AgNPs at 10 ppm, *C. amboinicus* (*Ca*) aqueous extract at 3%, *Ca*-AgNPs at 1 ppm, *Ca*-AgNPs at 10 ppm and distilled water (control). Growth parameters such as leaf number, leaf length, leaf width, bud diameter, root length and plant height of water hyacinth were measured at the time of application and 15 days after treatment (DAT). The root and shoot fresh weights and the root and shoot dry weights of water hyacinth plants were also recorded at 15 DAT. Leaf samples were collected on 5 DAT for biochemical analysis to determine the total chlorophyll content, total phenol content, carbohydrate content, and protein content. Superoxide dismutase activity was measured by analysing the leaf sample at 5 DAT.

Physiological and biochemical parameters

The photosynthetic rate and stomatal conductance were measured directly by using an LCA-4 - leaf chamber analyser or portable CO_2 analyser, manufactured by Analytical Development Co., Ltd., UK, at 5 DAT. The superoxide dismutase (SOD) activity (units/mg of protein) was estimated by the procedure described by Abedi and Pakniyat (2010). The chlorophyll content in the leaf samples was determined, following the method of Hiscox and Israelstam (1979). It was calculated by substituting the absorbance value (Arnon 1949) and expressed as mg/g.

$$\text{Chlorophyll a} = (12.7 \times A_{663} - 2.69 \times A_{645}) \times V/1000 \times 1/\text{Fresh weight}$$

$$\text{Chlorophyll b} = (12.7 \times A_{645} - 2.69 \times A_{663}) \times V/1000 \times 1/\text{Fresh weight}$$

$$\text{Total chlorophyll (a+b)} = (8.02 \times A_{663} \pm 20.2 \times A_{645}) \times V/1000 \times 1/\text{Fresh weight}$$

The total phenol content was assessed using Folin–Ciocalteu's method. Following incubation, the absorbance at 750 nm was measured using a spectrophotometer (Model-ELICO SL 218, Double beam, UV VIS, Spectrophotometer, India). The total phenolic content data are presented as milligrams (mg) of gallic acid equivalent weight (GAE) per 100 g of dry mass (Kamtekar *et al.* 2014). The total carbohydrate content was determined through the anthrone method (Hedge and Hofreiter 1962), and the protein content was assessed using Bradford's method (Bradford 1976). The results are expressed in mg/g of fresh weight.

Data analysis

The data obtained was subjected to analysis of variance (Panse and Sukhatme 1967). When the difference was significant, the critical difference was calculated at 1% and 5% using GRAPES software developed by Kerala Agricultural University (Gopinath *et al.* 2020).

RESULTS AND DISCUSSION

Characterization of biosynthesized AgNPs

The reduction of $AgNO_3$ by the leaf extracts in aqueous solution was verified through UV visible spectroscopy. The absorbance of the *Ph*-AgNPs was observed in the range of 430-450 nm (**Figure 1**). The

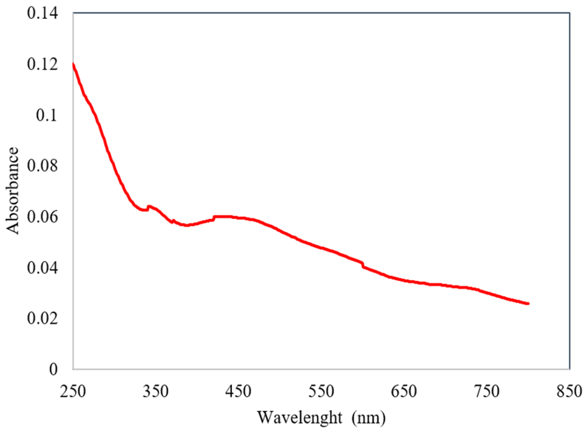

Figure 1. The UV-Visible spectrum of bio-synthesized *Parthenium hysterophorus* mediated silver nanoparticles

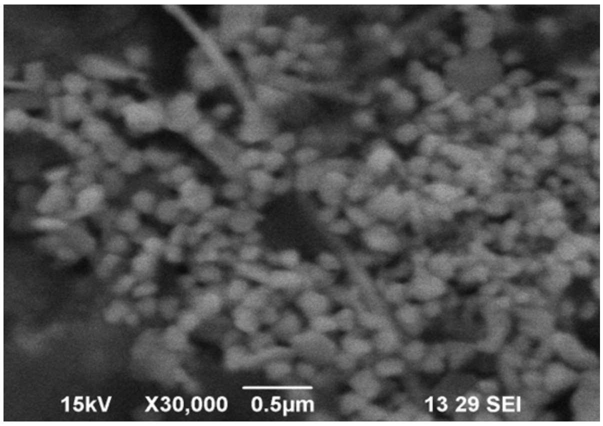

Figure 2. Scanning electron microscopy image of *Parthenium hysterophorus* mediated silver nanoparticles (*Ph*-AgNPs)

maximum size range of the AgNPs in the UV Vis spectrometer analysis was between 300 and 500 nm. This closely resembled the findings of Krithika *et al.* (2014). The reduction of Ag^+ to Ag^0 when exposed to plant extracts was qualitatively assessed by colour change. The surface plasmon resonance phenomenon was responsible for the shift in colour. The absorption band of surface plasmon resonance was due to the release of electrons from the metal NPs. Because of the collective oscillation of electrons on the metal surface triggered by light, AgNPs exhibit intense interactions with light (Panigrahi 2013). Earlier, Ag^0 NPs were synthesized by the reduction of Ag^+ ions using leaf extracts of *L. camara* (Shafaghat 2015; Ajitha *et al*. 2015). The biosynthesis of AgNPs, using *P. hysterophorus (*Kumar (2012) and *C. amboinicus* (Vanaja and Annadurai 2013) was reported earlier.

The average zeta potential (ZP) of -32.7 mV obtained from the analysis indicated that the *Ph*-AgNPs were stable, possibly due to the phytoconstituents in the leaf extract that could act as capping layers for the AgNPs, which might be responsible for the greater negative ZP. Negatively charged particles could repel one another, preventing agglomeration and resulting in NP stability. The proteins in the plant extracts also cap the AgNPs, preventing aggregation (Reddy *et al*. 2020). Thus, when the particle travels under the influence of Brownian motion, the hydrodynamic diameter provides information about the size of the core, the presence of any coating materials, and the solvent layer connected to the particle. As a result, the measured diameter of the particle is larger than its real size. Dynamic light scattering (DLS) revealed that the *Ph*-AgNPs had a particle size of 213 nm and a polydispersity index (PDI) of 0.52.

SEM provides additional insight into the shape and structure of AgNPs. The *Ph*-AgNPs were spherical in shape (**Figure 2**). Although the *Lc*-AgNPs and *Ca*-AgNPs were spherical, they were less uniform than the former. Similar SEM studies indicated that AgNPs synthesized from *L. camara, P. hysterophorus*, and *C. amboinicus* leaf extracts were spherical in shape (Vanaja and Annadurai 2013, Shafaghat 2015, Ahsan *et al*. 2020).

The X-ray diffraction (XRD) patterns of *Lc*-AgNPs, *Ph*-AgNPs, and *Ca*-AgNPs were examined and showed distinct peaks at different angles, with corresponding Miller indices (**Figure 3 a-c**). Sharp XRD peaks typically indicate crystallite materials (Bykkam *et al*. 2015). The AgNPs biosynthesized in this study were crystalline and had a face-centered cubic (FCC) crystal lattice structure, as confirmed by the XRD peaks (**Figure 3 a,b,c**). The reactivity of AgNPs depends on their size, with smaller particles having higher activity and toxicity due to their greater penetration ability (Panacek *et al*. 2006). AgNPs of various sizes (20-80 nm) induced toxicity in *Arabidopsis thaliana* seedlings (Ma *et al*. 2010). The tendency to release silver ions increases as the size decreases (Nowack *et al*. 2010). The phytotoxicity response is significantly affected by the size, shape, and concentration of NPs (Siddiqi and Husen 2016).

Effect on water hyacinth growth

The aqueous extracts of *L. camara, P. hysterophorus*, and *C. amboinicus* at 3% and the biosynthesized NPs at 1 ppm and 10 ppm affected the growth of water hyacinth (**Table 1**). It was found that the *Ph*-AgNPs affected water hyacinth growth in a concentration-dependent manner, with a notable effect on the number of leaves and bud diameter at 6 DAT and on the length and width of leaves at 9 DAT

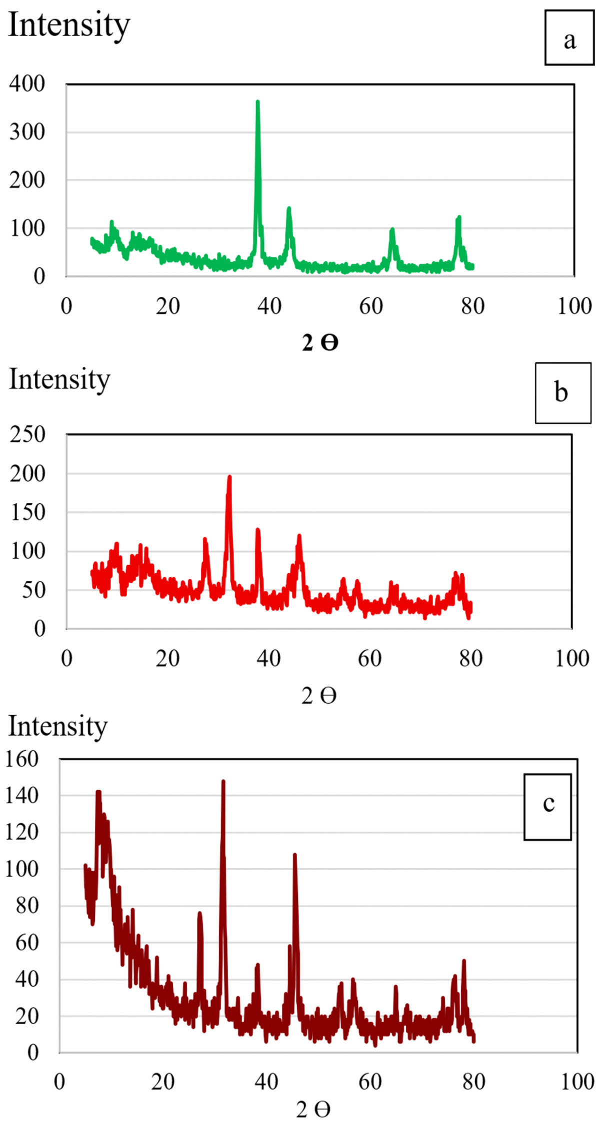

Figure 3. X-ray diffraction spectroscopy of bio-synthesized silver nanoparticles

a. *Lantana camara* mediated silver nanoparticles b. *Parthenium hysterophorus* mediated silver nanoparticles and c. *Coleus amboinicus* mediated

(**Figure 4**). Among the treatments, *Ph*-AgNPs at 10 ppm inhibited the growth of water hyacinth from 6 DAT to a 100% reduction in the biomass of water hyacinth within 15 DAT (**Table 1**). Abiotic stress can negatively affect plant development, growth, and performance by causing changes at the morphological, physiological, biochemical, and molecular levels. Oukarroum *et al.* (2013) reported a notable increase in the formation of intracellular ROS with the exposure of duckweed (*Lemna gibba*) to 1 and 10 mg/L AgNPs. The induced oxidative stress was connected to the accumulation of Ag within the plant cells of *L. gibba* and corresponded to the increase in the concentration of AgNPs in the medium.

At three-days post-treatment with *Ph*-AgNPs at 10 ppm, water hyacinth plants displayed chlorotic and necrotic symptoms, with leaf wilting and rolling from the margins (**Figure 4**). The entire leaf then became necrotic, resulting in the drooping and drying of the entire plant. The water hyacinth growth decreased due to a reduction in leaf dimensions and bud diameter, which could be attributed to the uptake of *Ph*-AgNPs. Previous studies reported similar growth inhibition effects on *Lemna minor* and *Lemna paucicostata* upon exposure to chemically synthesized AgNPs (Gubbins *et al.* 2011, Kim *et al.* 2011a, Kim *et al.* 2011b). Plants treated with AgNPs had shorter root hairs (Mittler 2002, Nel *et al.* 2006). The *Arabidopsis thaliana*, when exposed to AgNPs, could exhibit reduced root development and altered cell walls or cell shapes (Geisler-Lee *et al.* 2014). When exposed to chemically reduced AgNPs for 14 days, *Lemna minor* and *Pontederia crassipes*, experienced significant growth inhibition. Accumulation of AgNPs in plant tissues and roots led to necrosis and disrupted metabolic processes, resulting in reduced growth. The toxicity of AgNPs increases with increasing exposure time (Gubbins *et al.* 2011, Rani *et al.* 2016). Heavy metals were found to affect the root growth, development, and relative growth rate of *P. crassipes* and *Pistia stratiotes* plants (Odjegba and Fasidi 2007).

Plant height is a key indicator of plant growth. The use of *Ph*-AgNPs had a significant impact on the growth of water hyacinth at both concentrations tested. Application of 10 ppm *Ph*-AgNPs resulted in a significant decrease in plant height, root length, root and shoot fresh weight, and root and shoot dry weight, ultimately leading to complete growth inhibition (**Table 1** and **2**).

Effect on physiological parameters of water hyacinth

Metal stress alters enzymes that lead to chlorophyll degradation, resulting in yellowing, necrotic spots, and wilting of leaves. This affects plant photosynthesis, stomatal conductance, and carbohydrate and protein levels. The present study revealed that the application of 10 ppm *Ph*-AgNPs significantly decreased the total chlorophyll content, photosynthetic rate, stomatal conductance, carbohydrate content, and protein content in water hyacinth leaf tissue at 5 DAT (**Table 3, Figure 5**). Silver nanoaprtilces can disrupt the thylakoid membrane structure, which is crucial for photosynthesis, and can also affect the fluidity and permeability of cell membranes, influencing nutrient uptake and potentially leading to reduced chlorophyll synthesis (Qian *et al.* 2013). However, there was a noticeable increase in the total phenol content in the presence of *Ph*-AgNPs at both concentrations, with the maximum increase observed at 10 ppm (**Figure 5**). In response to metal stress, plants produce higher levels of phenols (Dudjak *et al.* 2004). Phenols play a role in plants growing under heavy metal stress by acting as antioxidants. Water hyacinth plants treated with synthetic and biosynthesized AgNPs increased the total phenol content (Rani *et al.* 2016). Synthetic AgNP treatment of castor resulted in increased contents of phenols and phenolic acids (Jyothsna and Rani 2013).

AgNPs inhibited the activity of photosynthetic pigments in the aquatic plant, *Spirodela polyrhiza* (Jiang *et al.* 2012). Exposure to AgNP at 0.002 mg/L for 4 days increased oxidative stress in Seagrass, while exposure to AgNP at 0.02 mg/L for 8 days severely damaged cell organelles and photosystem II (PS II) (Mylona *et al.* 2020). A decrease in carbohydrate content in water hyacinth was noted after 5 days of application of synthetic AgNPs, possibly because of a decrease in chlorophyll content that indirectly affects photosynthesis (Rani *et al.* 2016). A reduction in protein concentration can occur due to the degradation of preexisting proteins and a decrease in protein synthesis, which can serve as a biomarker for metal stress in plants (Mane *et al.* 2011).

The uptake of AgNPs disrupts the balance of water and small molecules, reduces photosynthetic activity, decreases photosynthetic efficiency, increases ROS production, and damages chloroplasts, potentially leading to plant growth retardation or death in *A. thaliana* (Qian *et al.* 2013). A similar study showed that water hyacinth plants treated with higher concentrations of AgNPs exhibited increased SOD activity due to metal stress (Rani *et al.* 2016). AgNPs cause oxidative stress in plants through the generation of ROS (Mittler 2002; Nel *et al.* 2006). Elevated SOD activity indicates oxidative stress-induced ROS imbalance, contributing to photosynthetic damage and reduced chlorophyll content and activity (Xu *et al.* 2025). In

Table 2. Root and shoot weight of water hyacinth plants as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs at 15 DAT

Treatment	Root fresh weight (g/pot)	Root dry weight (g/pot)	Shoot fresh weight (g/pot)	Shoot dry weight (g/pot)
Lc aq. extract 3%	16.90 ^{d}	1.65 ^{d}	21.33 ^{e}	1.64 ^{e}
Lc-AgNPs 1 ppm	36.91 ^{a}	3.27 ^{a}	36.29 ^{bc}	2.59 ^{b}
Lc-AgNPs 10 ppm	31.50 ^{b}	2.90 ^{b}	37.97 ^{b}	2.70 ^{b}
Ph aq. extract 3%	23.51 ^{c}	2.10 ^{c}	33.72 ^{c}	2.42 ^{c}
Ph-AgNPs 1 ppm	10.33 ^{f}	0.87 ^{e}	14.72 ^{f}	0.87 ^{f}
Ph-AgNPs 10 ppm	0 ^{g}	0 ^{f}	0 ^{g}	0 ^{g}
Ca aq. extract 3%	25.64 ^{c}	2.22 ^{c}	29.28 ^{d}	2.54 ^{bc}
Ca-AgNPs 1 ppm	21.92 ^{c}	2.02 ^{c}	33.04 ^{c}	2.57 ^{bc}
Ca-AgNPs 10 ppm	14.15 ^{de}	2.03 ^{c}	21.43 ^{e}	1.58 ^{e}
Distilled water	37.66 ^{a}	3.40 ^{a}	43.37 ^{a}	3.53 ^{a}
LSD (p=0.05)	2.893	0.274	3.445	0.165

Lc- Lantana camara, *Ph- Parthenium hysterophorus*, and *Ca-Coleus amboinicus;* aq. extract-aqueous extract AgNPs- Silver nanoparticles; DAT – days after treatment

Table 1. Growth parameters of water hyacinth as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs

Growth parameters	Number of leaves/plants		Length of leaves (cm)		Width of leaves (cm)		Bud diameter (cm)		Root length (cm)		Plant height (cm)	
	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT	0 DAT	15 DAT
Lc aq. extract. 3%	5.2	6.33 (2.6) ^{c}	5.0	5.80 (2.51) ^{cd}	6.6	6.82(2.70) ^{cd}	6.5	6.35(2.62) ^{bcd}	20.9	19.6(4.48) ^{e}	16.4	18.1(4.32) ^{b}
Lc-AgNPs 1 ppm	5.8	9.33 (3.14) ^{b}	6.2	6.39 (2.62) ^{ab}	7 .6	7.87(2.89) ^{abc}	6.6	7.67(2.85) ^{ab}	23.6	24.7(5.02) ^{c}	17.9	19.5(4.47) ^{ab}
Lc-AgNPs 10 ppm	5.0	8.83 (3.05) ^{b}	5.9	6.14 (2.58) ^{abc}	7.0	7.23(2.78) ^{bcd}	6.8	7.7(2.86) ^{a}	23.8	24.6(5.01) ^{c}	16.6	18.8(4.40) ^{ab}
Ph aq. extract 3%	5.3	6.67 (2.68) ^{c}	5.9	4.67 (2.27) ^{e}	7.5	7.55(2.83) ^{bc}	7.9	5.58(2.46) ^{cde}	22.9	18.5(4.37) ^{f}	16.5	18.3(4.33) ^{b}
Ph-AgNPs 1 ppm	4.5	4.50 (2.23) ^{d}	5.5	4.40 (2.21) ^{e}	6.7	6.33(2.61) ^{d}	6.4	4.68(2.27) ^{e}	24.9	18.9(4.41) ^{ef}	16.1	14.7(3.89) ^{c}
Ph-AgNPs 10 ppm	4.5	0 (0.7) ^{e}	5.6	0 (0.7) ^{f}	7.0	0 (0.7) ^{e}	6.4	0 (0.7) ^{f}	25.0	0(0.7) ^{g}	17.6	0(0.7) ^{d}
Ca aq. extract 3%	4.5	9.33 (3.14) ^{b}	5.4	6.25 (2.60) ^{ab}	7.0	7.37(2.80) ^{bc}	6.6	6.75(2.69) ^{abc}	22.7	23.0(4.85) ^{d}	16.1	18.3(4.34) ^{b}
Ca-AgNPs 1 ppm	5.0	8.83 (3.05) ^{b}	5.9	6.07 (2.56) ^{bc}	7.3	8.10(2.93) ^{ab}	6.9	7.97(2.91) ^{a}	25.0	28.1(5.35) ^{b}	16.6	19.0(4.41) ^{ab}
Ca AgNPs 10 ppm	5.3	8.33 (2.97) ^{b}	6.3	5.53 (2.46) ^{d}	8.0	8.17(2.94) ^{ab}	7.0	5.43(2.43) ^{de}	25.8	22.1(4.76) ^{d}	17.3	19.2(4.44) ^{ab}
Distilled water	5.5	11.33(3.44) ^{a}	5.9	6.47 (2.64) ^{a}	7.1	8.88(3.06) ^{a}	6.7	7.97(2.91) ^{a}	26.0	29.7(5.49) ^{a}	18.0	19.9(4.52) ^{a}
LSD (p=0.05)	NS	0.205	NS	0.077	NS	0.189	NS	0.233	NS	0.111	NS	0.178

Lc- Lantana camara, *Ph- Parthenium hysterophorus*, and *Ca-Coleus amboinicus*
aq. extract-aqueous extract AgNPs- Silver nanoparticles; DAT – days after treatment

Table 3. Physiological parameters of water hyacinth as influenced by treatment with different aqueous extracts and bio-synthesized AgNPs at 5 DAT

Treatment	Photosynthetic rate (μmole CO_2 /m²/s)	Stomatal conductance (mmole H_2O /m²/s)	Chlorophyll (mg /mL FW)	SOD (units/mg protein)
Lc aq. extract 3%	19.74 f	843.00 f	1.15 cd	428.17 c
Lc-AgNPs 1 ppm	25.86 c	1284.67 d	1.16 cd	372.74 e
Lc-AgNPs 10 ppm	25.37 c	1257.33 d	1.31 a	400.15 d
Ph aq. extract 3%	23.29 d	925.67 e	1.15 cd	411.42 d
Ph-AgNPs 1 ppm	22.26 e	886.33 ef	1.13 d	440.58 b
Ph-AgNPs 10 ppm	17.69 g	598.67 g	0.49 e	474.68 a
CA aq. extract 3%	26.88 ab	1466.67 b	1.29 ab	335.18 f
Ca-AgNPs 1 ppm	26.23 bc	1447.33 bc	1.22 bc	364.86 e
Ca-AgNPs 10 ppm	25.64 c	1380.00 c	1.10 d	403.38 d
Distilled water	27.70 a	1579.67 a	1.36 a	319.40 g
LSD (p=0.05)	1.002	67.890	0.073	11.396

Lc- Lantana camara, *Ph- Parthenium hysterophorus,* and *Ca-Coleus amboinicus*
aq. extract-aqueous extract; AgNPs- Silver nanoparticles; DAT – days after treatment

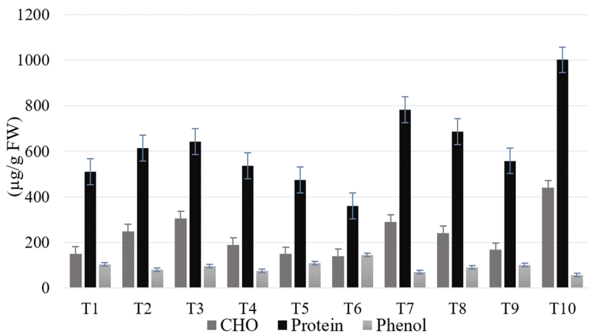

Figure 5. Carbohydrate, protein and phenol content of water hyacinth (µg/g FW) as influenced by different treatments.

T_1- *Lantana camara* aqueous extract at 3 percent, T_2- *Lantana camara* mediated silver nanoparticles at 1 ppm, T_3- *Lantana camara* mediated silver nanoparticles at 10 ppm, T_4- *Parthenium hysterophorus* aqueous extract at 3 %, T_5- *Parthenium hysterophorus* mediated silver nanoparticles at 1 ppm,, T_6- *Parthenium hysterophorus* mediated silver nanoparticles at 10 ppm, T_7- *Coleus amboinicus* aqueous extract at 3 %, T_8- *Coleus amboinicus* mediated silver nanoparticles at 1 ppm,, T_9- *Coleus amboinicus* mediated silver nanoparticles at 10 ppm, T_{10}- Distilled water (control)

the present study, the SOD content increased with the addition of 10 ppm Ph-AgNPs, followed by the addition of 3% aqueous *L. camara* extracts (**Table 3**). An increase in SOD activity in water hyacinth was noted with the use of *L. camara* aqueous extracts at a concentration of 3%. This could be considered as one of the plant's antioxidant responses to phytotoxins present in *L. camara* leaf extract. SOD activity in the leaves of water hyacinth correlated with the accumulation of H_2O_2 and the increase in the degree of membrane peroxidation (Zheng *et al.* 2006).

Conclusion

The 10 ppm *Ph*-AgNPs effectively suppressed photosynthetic rate, stomatal conductance, chlorophyll content, total phenol content, carbohydrate content, protein content and SOD activity and affected water hyacinth growth, *viz.*, number of leaves, length and width of leaves, bud diameter, root length, height of plants, root and shoot fresh weight and dry weight. Thus, AgNPs (10 ppm) biosynthesized using the noxious weed *Parthenium hysterophorus* could be effectively utilized as a component of integrated management of another problematic aquatic weed, water hyacinth.

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RESEARCH ARTICLE

Allelopathic potential of *Eucalyptus camaldulensis* Dehnh. on germination of obligate root-parasitic broomrape (*Orobanche cernua* Loefl.)

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ABSTRACT

In the present study, an assessment of allelopathic effect of *Eucalyptus camaldulensis* Dehnh. and its various derivatives was assessed on the germination of obligate-root and holo-parasitic weed, nodding broomrape (*Orobanche cernua* Loefl.). Optimized *in vitro O. cernua* germination assays were conducted under different experimental setups, to determine the allelopathic potential of sapling, leaf-litter extract, plantation-soil, distilled *Eucalyptus* oil and purified eucalyptol of *E. camaldulensis*. A considerable and varying levels of inhibitory allelopathic impact on *O. cernua* seed germination was observed with all tested materials of *E. camaldulensis*. These findings indicate the possibility to use of allelopathic potential of *E. camaldulensis* for managing the underground root parasitic-weed infestation in various agricultural crops.

Keywords: Allelopathy, Broomrape, *Eucalyptus camaldulensis*, *Orobanche cernua* and Weed management

INTRODUCTION

Eucalyptus camaldulensis Dehnh., an indigenous to Australia, is a large, fast-growing ever-green tree (Sani *et al.* 2014). Owing to its faster growth, wider eco-adaptability, higher productivity and its commercial application, various *Eucalyptus* sp. have been introduced in many countries (Davidson 1995). One of most characteristic features of *Eucalyptus* plantation is its ability to reduce the diversity and productivity of underneath crops and species in its vicinity (del Moral and Muller 1970). The suppressive effect of *Eucalyptus* is either due to its direct- or indirect-impact on ground vegetation (Bowman and Kirkpatrick 1986). The direct-impact of *Eucalyptus* has been attributed primarily due to its allelopathic effects on other plants (Turnbull 1999). The broad-spectrum negative allelopathic impact of *Eucalyptus* was reported on the growth and survival of various herbs, agronomical-crops, weeds, forest-crops, algae, microbes (*i.e.* bacteria and fungi) as well as certain avian species (Goded *et al.* 2019). However, reports of allelopathic impact of *Eucalyptus* on obligate-root and holo-parasitic weed, broomrape (*Orobanche cernua* Loefl.) are scanty.

Broomrape parasitizes the diverse-range of crops and pastures (Das *et al.* 2020). Global revenue losses of \$1.3-2.6 billion/annum have been projected due to overwhelming damages (0-100% crop failures) owing to broomrape infestation (Ahmad *et al.* 2018). To overcome these losses, a number of control-strategies have been evaluated in the past (Cartry *et al.* 2021). However, none of the available control measures for broomrape infestation can be considered as practically viable, foolproof, effective, economical and eco-friendly. This is primarily due to broomrape hybrid traits (weed and root-parasite), achlorophyllous nature, predominant subterranean life, close proximity with host roots, exclusive uptake of host's resources *via* haustoria, growth synchronization with the specialized range of host cultivation, complex mechanisms of seed dispersal and germination, fecundity (up to 5,00,000 seeds/plant), physiological seed-dormancy, tiny seed size, eternal seeds longevity and existence of enormous seed-bank in infested fields (Das *et al.* 2020, Cartry *et al.* 2021). Thus, the only precautionary and sustainable way to effectively minimise the devastating damages caused by *Orobanche* sp. is through the use of natural product(s) having potential orobanchicidal effect. In this context, allelopathy and allelochemical(s) potential of *E. camaldulensis* needs to be evaluated.

Thus, a preliminary study was conducted to evaluate the allelopathic impact of *E. camaldulensis* sapling, leaf litter extract, plantation soil, distilled *Eucalyptus* oil and purified eucalyptol of *E. camaldulensis* on *in vitro* germination of nodding broomrape (*O. cernua*) under laboratory-conditions.

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MATERIALS AND METHODS

A study was conducted in the Plant Science laboratory, ITC Life Science and Technology Centre (LSTC), Bengaluru, Karnataka, India during October, 2022 to June, 2023. In order to conduct the study on allelopathic potential of *E. camaldulensis*: *i.* approximately 3 months old (30-32 cm) *E. camaldulensis* saplings (ITC clone no. 1803); ii. healthy leaf-litters from 4 years old *E. camaldulensis* tree plantation and top-layered (0-30 cm depth) soil (from the field with a history of >10 years of *E. camaldulensis* plantation) were procured from *Eucalyptus* plantation field of ITC-Paperboards and Specialty Papers Division (PSPD), Bhadrachalam at Jagannadhapuram (17.6071° N, 80.7533° E), Kotthagudem district, Telangana, India. The collected *E. camaldulensis* leaves and soil sample (that was air-dried and sieved through a 2 mm mesh) were stored in tight-seal dark containers until use; iii. GR_{24} (Catalogue#racGR24), a synthetic strigol analog, was acquired from Strigolab S.r.l., Italy; iv. *Eucalyptus* oil (EO) was sourced from Ultra International Limited, Uttar Pradesh (U.P.), India; v. GC-grade eucalyptol (Catalogue # r46090) was procured from Sigma-Aldrich (St. Louis, USA); vi. *O. cernua* seeds were collected from its mature flower spikes that feeds off the cultivated tobacco (*Nicotiana tabacum* L.) grown during 2021-22 season at Rajahmundry, India (17.0005° N, 81.8040° E). The harvested *O. cernua* seeds were stored in darkness at 25 °C until utilized.

O. cernua seed viability was assessed by 2,3,5-triphenyl tetrazolium chloride (TTC) method (Thorogood *et al.* 2009). Autoclaved distilled water (DW), 10 mm glass filter paper disc (GFPD; Whatman; GE Healthcare) and 47 mm filter-papers (Whatman) were used throughout the study. Prior to usage, *O. cernua* seeds underwent surface sterilization by treating them with a solution of 1% (*v/v*) NaOCl for duration of 2 min. Subsequently, the seeds were thoroughly rinsed with DW and left to air-dry at room temperature. Fifty surface-sterilized *O. cernua* seeds were evenly distributed on GFPD pre-treated with distilled water and placed in a petri dish lined with two layers of moistened filter paper. Each petri dish contained four GFPD with *O. cernua* seeds, which were then covered with aluminium foil and incubated at 25 °C for a period of three days. Non-viable heat-killed (HK, microwaved for 10 min) *O. cernua* seeds were taken as *negative control*. Following this, *O. cernua* seeds were soaked in a 1% TTC solution (Himedia) and then placed in a dark environment at 37 °C for 24 h. Subsequently, *O. cernua* seeds were immersed in a 0.4% (*v/v*) NaOCl solution for 1 min, rinsed thoroughly with DW and examined under a compound microscope with a 4× magnification (Leica DM1000, Leica Microsystems, USA). Of note, due to dehydrogenases activity of live cells, TTC forms a red colored 1,3,5-triphenylformazan precipitate. Thereby, *O. cernua* seeds that were either stained with bright-yellow or orange colour or left unstained has been scored as viable and non-viable, respectively.

A modified laboratory scale '*co-culture*' method was developed as described earlier (Ye *et al.* 2020) with the certain changes, wherein *O. cernua* seeds were co-cultured with *E. camaldulensis* sapling in a petri dish. Four GFPDs were placed in each 150 mm petri dish (covered with a double layer 47 mm filter-paper), with each GFPD holding around 50 surface sterilized *O. cernua* seeds. To create a suitable environment for germination, filter papers were moistened with 5 ml of DW. Sterilized vermiculite (~ 25 g) was added in each petri dish. One *E. camaldulensis* sapling per petri dish was planted by passing it through a hole made in peripheral frame of both petri dish container and lid and allowed to stand it vertically throughout the experiment (hereafter stated as *E. camaldulensis* conditioned seeds, ECS). Likewise, a similar treatment but without *E. camaldulensis* sapling was also used (hereafter stated as non-eucalyptus conditioned seeds, NECS). The petri dishes, sealed with parafilm and covered with aluminium-foil, were incubated at 25 °C for 7 days. Afterward, GFPD with pre-conditioned ECS and NECS (dried to eliminate excess water) were spread on fresh GFPD, transferred to a new petridish (covered with a double layer 47 mm filter-paper) and moistened with 5 ml of 10 mg / L GR_{24} or 0.1% (*v/v*) acetone (*solvent control*) and further incubated at 25 °C for 3 days. Sterilised DW was added periodically to each petri dish to maintain the enough moisture throughout the germination assay. After conducting a comprehensive 10-day test, *O. cernua* seeds with an emerged radicle were scored under a compound microscope (Leica) with a 4× magnification. The calculated cumulative germination rate (CGR, in %) of *O. cernua* seeds was normalised to aforesaid average seed viability (%) determined through TTC analysis.

In vitro O. cernua seed germination assay was conducted following the methods outlined in a previous study (Louarn *et al.* 2012) with specific adjustments made. In every test conducted, four GFPDs were placed in each 150 mm petri-dish (covered with a double layer 47 mm filter paper), with each GFPD holding around 50 surface-sterilized

O. cernua seeds. Each petri dish was moistened with 5 ml of DW or corresponding test reagent. Notably in each experiment, non-viable heat HK seeds, were also included as a *negative control*. Fresh preparations of each test-reagent and its dilution were made prior to analysis in order to avoid any potential degradation of their inherent bio-actives.

Experiment 1: *E. camaldulensis* leaf litter extract (LLE) effect on *O. cernua* seeds germination

E. camaldulensis leaf litters were collected and washed thoroughly with DW (to remove the impurities and dirt-particles). Cleaned leaf litters were dried in a hot air incubator (Lab India Instruments Pvt. Ltd., India) at 60 °C until they become fully dehydrated. The dried leaf litter was ground using a laboratory grinder and sieved (through a 0.6 mm mesh) to achieve a fine powder (particle size ~500 ìm). The obtained leaf powder was boiled with DW [1:5 (*w/v*)] at 80 °C for 20 min. The resulting LLE was filtered through filter paper (Whatman No. 1) and subsequently combined with DW to attain the desired concentrations (10%, 25%, 50%, 75%, and 100%) and preserved in glass vials. *O. cernua* seeds were dispersed on a GFPD pretreated with either DW (*i.e.* NECS) or with specific aforesaid concentration of LLEs (*i.e.* ECS).

Experiment 2: *E. camaldulensis* field plantation soil effect on *O. cernua* seeds germination

The petri-dish harbouring *O. cernua* seeds were dispersed on a GFPD pretreated with DW was prefilled with ~25 g fine sieved test soil. Notably, soil sample was also collected from the demonstration / greenhouse field (with no previous history of any *Eucalyptus* plantation or broomrape infestation) of ITC-LSTC, Bengaluru (labelled as non-eucalyptus soil). Hereafter, corresponding *O. cernua* seeds that were pre-conditioned on *Eucalyptus* and non-eucalyptus soils were stated as *E. camaldulensis* soil conditioned-seeds (ESCS) and non-eucalyptus soil conditioned-seeds (NESCS), respectively. Approximately 10 ml DW was added in each petri-dish to keep the soil-moist.

Experiment 3: Eucalyptus oil (EO) effect on *O. cernua* seeds germination

O. cernua seeds were dispersed on a GFPD pretreated with either DW (*i.e.* CU) or with specific concentration of distilled EO (*i.e.* 0.01%, 0.02%, 0.03%, 0.04% and 0.05%; collectively stated as CT). Notably, various dilutions of EO were prepared in 0.02% (*v/v*) non-ionic surfactant, APSA-80 (*Amway*, India).

Experiment 4: Purified eucalyptol (EL) effect on *O. cernua* seeds germination

O. cernua seeds were dispersed on a GFPD pretreated with either DW (i.e. CU) or with specific concentration of purified EL (i.e. 0.1%, 0.25%, 0.5%, 0.75% and 1%; collectively stated as CT).

For every aforementioned trial, each petri-dish was incubated at 25 °C for 7 days. After this, GFPD with preconditioned *O. cernua* seeds were carefully blotted to eliminate any excess water or test reagent. The preconditioned *O. cernua* seeds were then spread onto fresh GFPD, kept in a new petri dish (covered with two layers of filter paper), moistened with either 5 ml of 10 mg/L GR_{24} or 0.1% (*v/v*) acetone (*solvent-control*) and incubated at 25 °C for 3 days. At the end of the test period, *O. cernua* seeds were scored for its germination (*as described above*).

Each experiment was evaluated in three biological replicates (~50 seeds per measurement) and repeated twice. Results are expressed as means ± standard deviations (SDs). Statistically significant (p=0.05) difference between comparative groups was analysed by Kruskal-Wallis test.

RESULTS AND DISCUSSION

Orobanche sp. germination has been considered to be a two-stage process, characterised by an independent '*pre-conditioning*' phase, during which it becomes susceptible to natural / synthetic GS, followed by a host-dependent '*chemical-stimulation*' phase, during which the radicle protrusion begins (Joel *et al.* 1991). As the germination-potential of *O. cernua* seed is developed during the pre-conditioning period, thereby any observed variation in its CGR resulting from the '*test*' preconditioning media can be used to ascertain their precise influence on *O. cernua* seed germination. With this background, we investigated the allelopathic capacity of *E. camaldulensis* saplings and other allelopathy testing materials, *viz.* LLE; plantation-soil; distilled EO and purified EL as a pre-conditioning media on *in vitro* germination of *O. cernua* under prescribed assay conditions. At foremost, seed viability test of *O. cernua* seeds were quantified (~76%) by TTC method, which was used as a correction factor in normalising the CGR in all subsequent experiments.

Effect of co-culturing with *E. camaldulensis* saplings on *O. cernua* seed germination

The study on the direct impact of growing *E. camaldulensis* in the vicinity of *O. cernua (co-culture)* recorded a CGR of ~58% (**Figure 1**). Conversely, the CGR of *O. cernua* seeds pre-conditioned in the

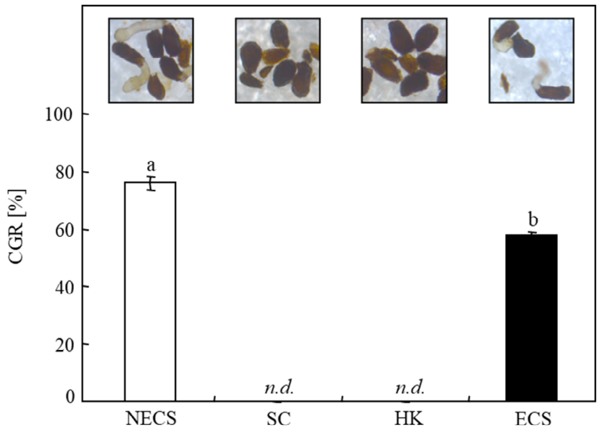

Figure 1. Allelopathic effect of *E. camaldulensis* saplings '*co-culture*' on *O. cernua* seed germination

The micrographs illustrate the representative *O. cernua* seeds / germlings at the end of test-period. The bar chart depicts the base corrected CGR (%), wherein distinct letters demonstrate statistically significant variations (p=0.05). ECS - *E. camaldulensis* conditioned seeds, NECS - non-eucalyptus conditioned seeds, SC – solvent control, HK - heat killed, CGR - cumulative germination rate and *n.d.* - not detected.

absence of *E. camaldulensis* sapling (stated as NECS) was observed to be ~76% (**Figure 1**). Comparative studies (NECS *vs* ECS) revealed a prominent decline (~24%) in CGR of ECS supporting observations made with other crops (Shivanna *et al.* 1992; Lisanework and Michelsen 1993).

Effect of *E. camaldulensis* leaf litter extract (LLE) on *O. cernua* seed germination

O. cernua seeds were incubated with either distilled water (hereafter stated as CU) or with different concentrations of LLE (i.e. 10%, 25%, 50%, 75% and 100%, correspondingly abbreviated as LLE_{10}, LLE_{25}, LLE_{50}, LLE_{75} and LLE_{100} respectively; collectively stated as CT) under prescribed assay-conditions(**Figure 2A**). The CGR of CU was observed to be ~76% (**Figure 2B**). For CT, a CGR of ~72%, ~67%, ~58%, ~43% and ~41% was observed for LLE_{10}, LLE_{25}, LLE_{50}, LLE_{75} and LLE_{100}, respectively (**Figure 2B**). Comparative analyses (CU *vs* CT) demonstrated a significant gradual decrease in

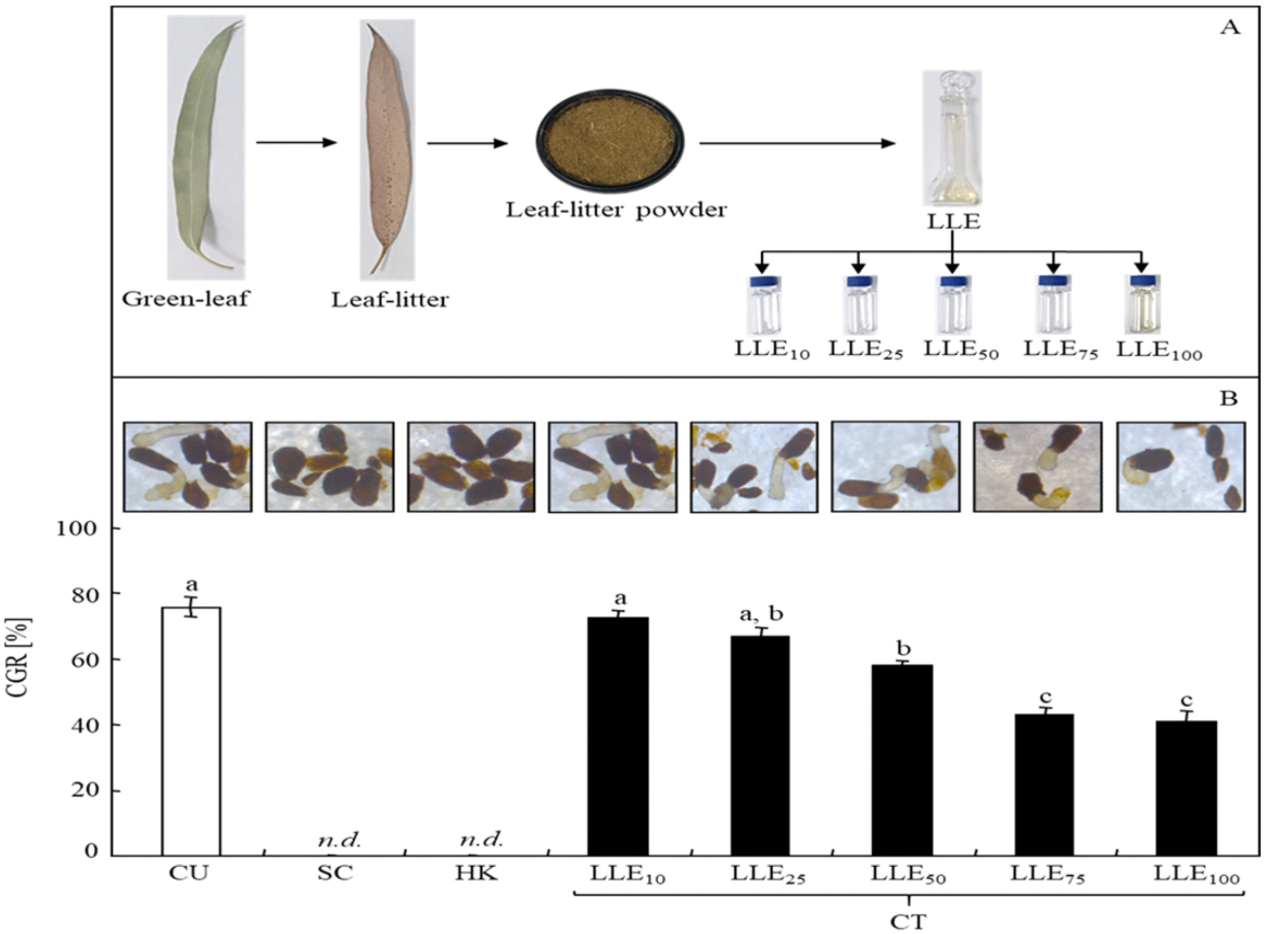

Figure 2. Allelopathic effect of *E. camaldulensis* leaf litter extract (LLE) on *O. cernua* seed germination

A. Flow chart depicts the preparation of *E. camaldulensis* LLE and its various dilutions (*i.e.* LLE_{10}, LLE_{25}, LLE_{50}, LLE_{75} and LLE_{100}). **B.** *O. cernua* seeds were pre-conditioned either in the absence (i.e. CU) or presence (i.e. CT) of various concentration of LLEs, followed by stimulation with 10 mg/L GR_{24} or 0.1% (*v/v*) Ac (*i.e.* SC) under specified assay conditions. The micrographs illustrate the representative *O. cernua* seeds/germlings at the end of test-period. The bar chart depicts the base-corrected CGR (%), wherein distinct letters demonstrate statistically significant variations (p=0.05). SC – solvent control, Ac - acetone, LLE – leaf litter extract, CU - conditioned untreated seeds, CT - conditioned treated seeds, HK - heat killed, CGR - cumulative germination rate and *n.d.* - not detected.

CGR of CT (~5%, 12%, and 24% at LLE_{10}, LLE_{25} and LLE_{50}, respectively), before stabilizing at a plateau (with a corresponding decline of ~44-46% at LLE_{75} and LLE_{100}). These results are in accordance with a dose-dependent inhibitory effect of *Eucalyptus* ALE on seeds/seedlings germination of different crops (Padhy *et al.* 2000), Djanaguiraman 2005, Akram *et al.* 2017, Sousa *et al.* 2018). In order to assess whether the observed inhibitory impact of LLEs display toxicity toward *O. cernua* seeds, we additionally measured the CT seeds viability. Our results demonstrated the null effect of *E. camaldulensis* LLEs on *O. cernua* seed viability at all tested concentrations (data not given here and can be obtained from authors) indicating that Ec LLEs only alters the ability of *O. cernua* seeds to germinate, without affecting their inherent viability.

Effect of *E. camaldulensis* plantation soil on *O. cernua* seed germination

The CGR of non-eucalyptus soil conditioned-seeds (NESCS) was observed to be ~72% (**Figure 3**). On the contrary, the CGR for *E. camaldulensis* soil conditioned-seeds (ESCS) was observed to be ~27% (**Figure 3**). Comparative analysis (NESCS *vs* ESCS) revealed a substantial decline (~63%) in CGR of ESCS. These results were also in agreement with recent findings, wherein *E. camaldulensis* infested soil has been reported to significantly reduce the growth of *Aloe barbadensis* Mill. plantations (Singh *et al.* 2021).

Effect of Eucalyptus oil (EO) as a pre-conditioning media on *O. cernua* seed germination

The evaluation of the impact of EO on *in vitro* germination of *O. cernua* seeds pre-conditioned either in DW (stated as CU) or different concentration of EO (*i.e.* 0.01%, 0.02%, 0.03%, 0.04% and 0.05%, correspondingly abbreviated as $EO_{0.01}$, $EO_{0.02}$, $EO_{0.03}$, $EO_{0.04}$ and $EO_{0.05}$, respectively; hereafter collectively stated as CT) resulted in CGR of CU to be ~76% (**Figure 4**). Regarding CT, a CGR of ~14%, ~8%, ~5%, 0% and 0% was observed for $EO_{0.01}$, $EO_{0.02}$, $EO_{0.03}$, $EO_{0.04}$ and $EO_{0.05}$, respectively (**Figure 5**). Comparative analyses (CU vs CT) demonstrated a significant gradual decrease in CGR of CT (~81%, ~90% and ~93% at $EO_{0.01}$, $EO_{0.02}$ and $EO_{0.03}$ respectively), before stabilizing at a plateau of complete inhibition (*i.e.* 100% inhibition at $EO_{0.04}$ and $EO_{0.05}$). These results confirmed the dose-dependent inhibition by EO (from *E. camaldulensis* as well as *E. citriodora* and *E. tereticornis*) of the germination of *P. hysterophorus* (Chaturvedi *et al.* 2012). Notably, no effect on *O. cernua* seed viability was observed at lower concentration of EO (*i.e.* $EO_{0.01}$, $EO_{0.02}$ and $EO_{0.03}$; Data not given here and can be obtained from authors). Overall, these results demonstrated EO exclusively inhibited *O. cernua* seed germination, without having any impact on its viability.

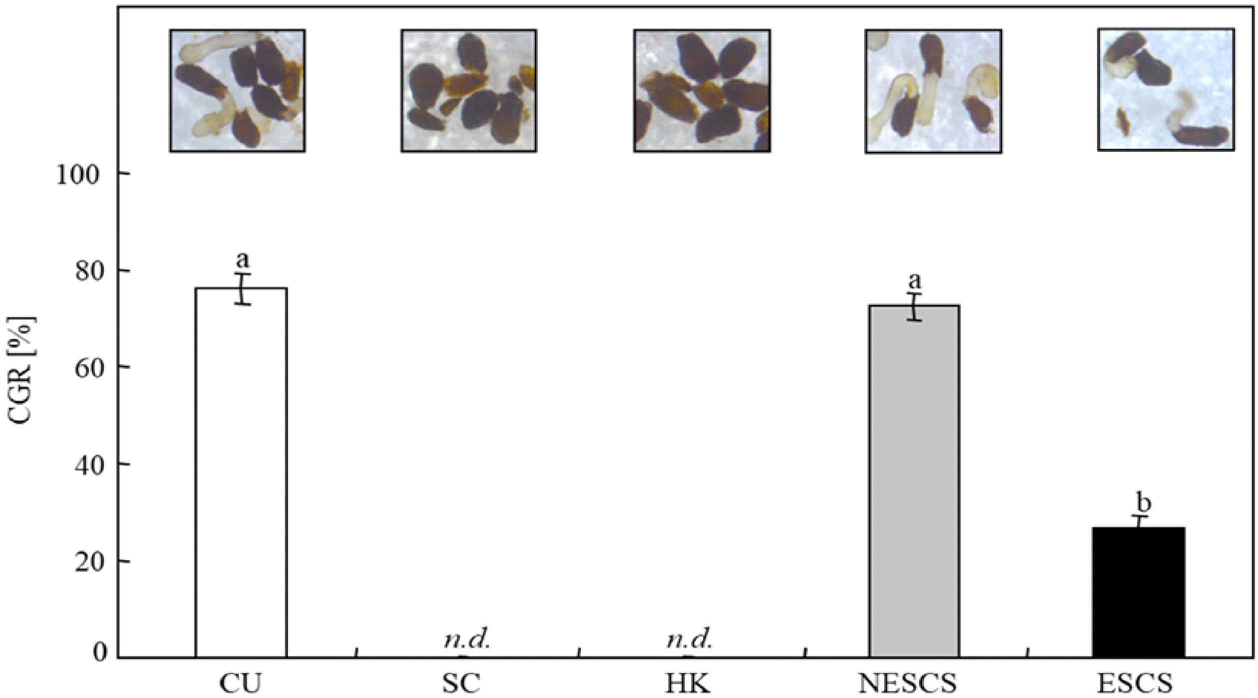

Figure 3. Allelopathic effect of *E. camaldulensis* field plantation soil on *O. cernua* seed germination

The micrographs illustrate the representative *O. cernua* seeds/germlings at the end of test period. The bar-chart depicts the base corrected CGR (%), wherein distinct letters demonstrate statistically significant variations (p=0.05). NESCS - non-eucalyptus soil conditioned seeds, ESCS - *E. camaldulensis* soil conditioned seeds, SC – solvent control, HK - heat killed, CGR - cumulative germination rate and *n.d.* - not detected.

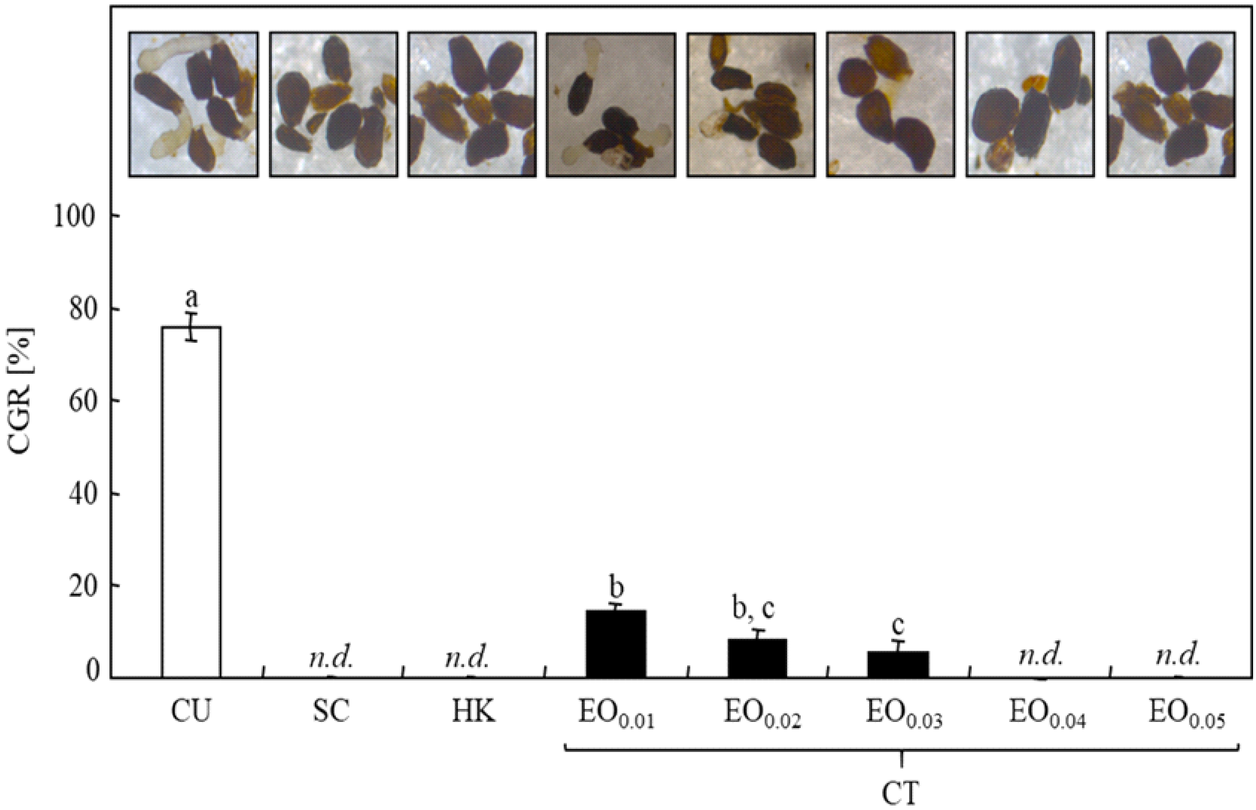

Figure 4. Allelopathic effect of Eucalyptus oil (EO) on *O. cernua* seed germination

The micrographs illustrate the representative *O. cernua* seeds / germlings at the end of test period. The bar chart depicts the base corrected CGR (%), wherein distinct letters demonstrate statistically significant variations (p=0.05). $EO_{0.01}$, $EO_{0.02}$, $EO_{0.03}$, $EO_{0.04}$ and $EO_{0.05}$ corresponds to EO at a concentration (*v/v*) of 0.01%, 0.02%, 0.03%, 0.04% and 0.05%, respectively. EO - *Eucalyptus* oil, CU - conditioned untreated seeds, CT - conditioned treated seeds, SC - solvent-control, HK - heat killed, CGR - cumulative germination rate and *n.d.* - not detected.

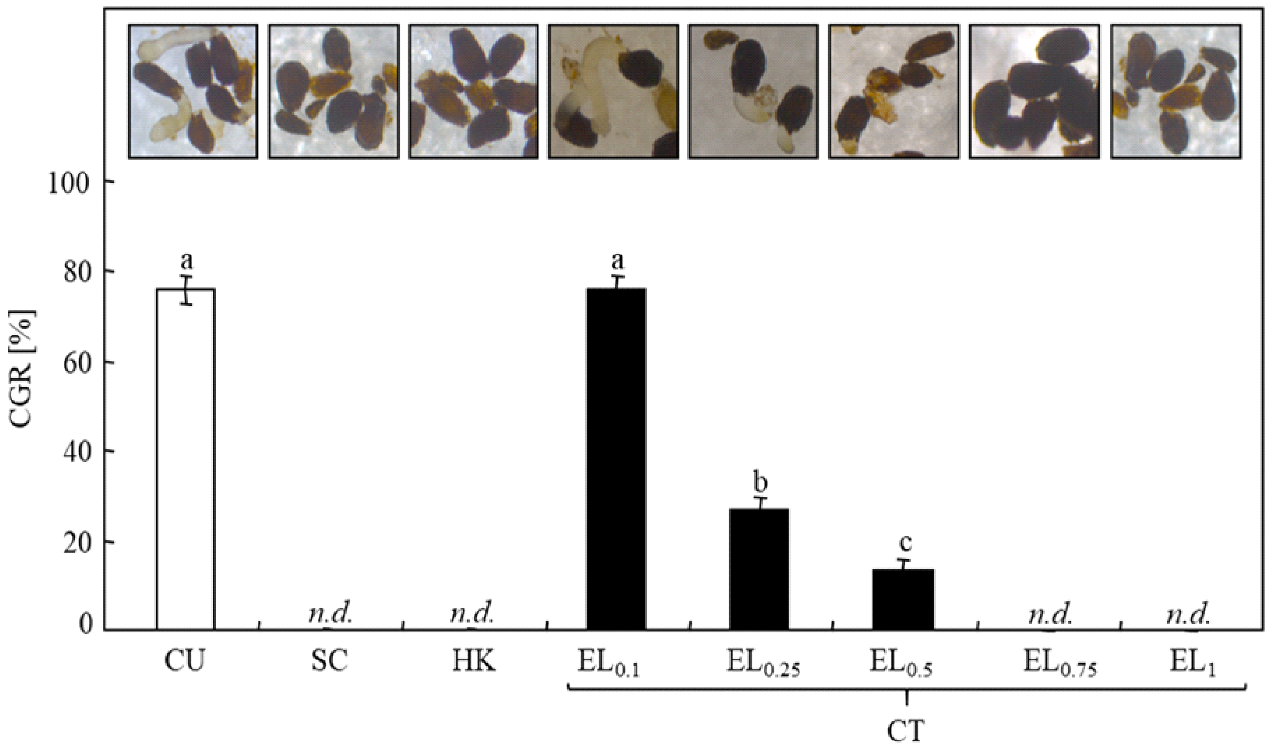

Figure 5. Allelopathic effect of purified eucalyptol (EL) on *O. cernua* seed germination

The micrographs illustrate the representative *O. cernua* seeds / germlings at the end of test period. The bar chart depicts the base corrected CGR (%), wherein distinct letters demonstrate statistically significant variations (p=0.05). $EL_{0.1,}$ $EL_{0.25}$, $EL_{0.5}$, $EL_{0.75}$ and EL_1 corresponds to EL at a concentration of 0.1%, 0.25%, 0.5%, 0.75% and 1%, respectively. EL - eucalyptol, CU - conditioned untreated seeds, CT - conditioned treated seeds, SC – solvent control, HK - heat killed, CGR - cumulative germination rate and *n.d.* - not detected.

Effect of purified eucalyptol (EL) on *O. cernua* seed germination

O. cernua seeds were incubated with either distilled water (hereafter stated as CU) or with different concentrations of EL (*i.e.* 0.1%, 0.25%, 0.5%, 0.75% and 1%, correspondingly abbreviated as $EL_{0.1}$, $EL_{0.25}$, $EL_{0.5}$, $EL_{0.75}$ and EL_1 respectively; collectively stated as CT). The CGR of CU was observed to be ~76% (**Figure 5**). Regarding CT, a CGR of ~76%, ~27%, 13%, 0% and 0% was observed for $EL_{0.1,}$ $EL_{0.25}$, $EL_{0.5}$, $EL_{0.75}$ and EL_1 respectively (**Figure 5**). Comparative analyses (CU vs CT) demonstrated a significant gradual decrease in CGR of CT (0%, ~65% and ~82% at $EL_{0.1,}$ $EL_{0.25}$ and $EL_{0.5}$, respectively), before stabilizing at a plateau of complete inhibition (i.e. 100% inhibition at $EL_{0.75}$ and EL_1). There was no impact on *O. cernua* seed viability at lower concentration of EL (*i.e.* $EL_{0.1,}$ $EL_{0.25}$ and $EL_{0.5}$; data not given here and can be obtained from authors). This study demonstrated that EL could serves a potential allelopathic agent against *O. cernua* seed germination. It is essential to identify unknown allelochemical(s) from EO through future extensive studies.

This study demonstrated the varying degree of negative allelopathic potential of *E. camaldulensis* saplings; leaf-litter extract; plantations-soil; *Eucalyptus* oil and eucalyptol on *O. cernua* seed germination indicating possibility for future screening and development of allelochemicals from *E. camaldulensis* to manage *O. cernua.*

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RESEARCH ARTICLE

Comparative phytochemical profiling of *Physalis longifolia* Nutt. leaves and fruits extracts: Insights from gas chromatography-mass spectrometry (GC-MS) analysis

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ABSTRACT

The aim of this study was to examine the bioactive compounds of *Physalis longifolia* Nutt. growing in northern part of India utilizing gas chromatography-mass spectrometry (GC-MS). The leaf extracts showed remarkable antioxidant activity in DPPH (2, 2-diphenyl-2-picrylhydrazyl hydrate) radical scavenging activity and FRAP (Ferric reducing anti-oxidant power assay) as compared to fruit extracts, evidenced by their lower IC_{50} value. The leaves and fruit extracts of *P. longifolia* included 25 different compounds, including saturated fatty acid esters, organosilicons, mono- and poly-unsaturated omega-6 fatty acids. Methyl linoleate (11.89%), methyl palmitate (20.38%), methyl stearate (22.90%), cyclotetrasiloxane (octamethyl) (18.99%), and heptadecanoic acid methyl ester (0.18%) are among the most prominent bioactive substances. The phytochemical and GC-MS profiling of *P. longifolia* leaves and fruits revealed the presence of bioactive compounds with important medicinal properties.

Keywords: Antioxidant, Bioactive compounds, Gas chromatography-mass spectrometry, Medicinal properties, *Physalis longifolia*

INTRODUCTION

Physalis longifolia Nutt., wild tomatillo or long leaf groundcherry, is a perennial herb that occurs throughout the continental U.S. and into southern Canada and northern Mexico (Kindscher *et al.* 2012). Its habitat includes old fields, open woods, and prairies, but it thrives in disturbed sites, including roadsides. Plants form colonies through the spread of underground rhizomes and it is often considered to be a weed because the plant is so common. Originally brought to California, *Physalis longifolia* Nutt. is now regarded as invasive there because of its quicker seeds and rhizomes dissemination (USDA 2011, Kindscher *et al.* 2012).

Native to North America and South Asia, its adaptability allows it to grow in diverse conditions, including sandy soils during *Kharif* in India where it is often seen as a weed (Singh *et al.* 2019). Traditionally, native American tribes such as the Acoma, Hopi and Zuni consumed its berries fresh or cooked. Historically, it has been used for various medicinal and culinary purposes, though species identification was often unclear, leading to confusion with related species Traditional uses of the herb *P. longifolia* are extensively reported as medicine, the Omaha and Ponca tribes generally using as local medicine to treat headache, stomach problems and to dress wounds (Kindscher *et al.* 2012). The fruits and flowers of the plant are also used in the stomach pain, constipation and herb paste is used in ear problems (Vipin and Ashok 2010).

Physalis longifolia is highlighted as a prominent weed due to its invasive nature and agricultural significance. This species spreads rapidly through both seeds and rhizomes, making it difficult to control in disturbed areas and cropping systems. Additionally, *P. longifolia* plays a key role in the transmission of zebra chip disease in potatoes. It serves as a preferred host for the potato psyllid (*Bactericera cockerelli*), which vectors the pathogen *Candidatus Liberibacter solanacearum*, posing a serious risk to solanaceous crops in the U.S. (Reyes Corral *et al.* 2021). Given its ecological impact and role in pest dynamics, *P. longifolia* is recognised as a prominent weed and hence effective management planning is necessary. The utilization of the weeds is considered to be one of the management approaches (Chandrasena and Rao 2018).

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Phytochemical studies have identified antioxidants in *Physalis* fruits, including anthocyanins in *P. ixocarpa* (Gonzalez-Mendoza *et al.* 2010), and carotenoids and withanolides in *P. peruviana* (Ramadan 2011). Similar research is recommended for related species like *P. longifolia*, which has shown anticancer, anti-proliferative, and anti-inflammatory effects due to its phytochemicals. It may also help manage chronic conditions like diabetes and neurological disorders (Huang *et al.* 2020).

Gas chromatography-mass spectrometry (GC-MS) effectively identifies and quantifies bioactive compounds in plant extracts by comparing mass spectra to reference databases, detecting volatile and semi-volatile compounds like alkaloids, flavonoids, terpenoids, and phenolics (Grover and Ptani 2013). It supports plant-based drug discovery in nutraceuticals and pharmaceuticals. *P. longifolia* remains underexplored, with no Indian GC-MS studies on its phytochemicals or bioactivity. Thus, this study was conducted with an objective to assess the phytochemical and antioxidant properties of its leaf and fruit extracts.

MATERIALS AND METHODS

Leaves and fruits of *Physalis longifolia* Nutt. were collected from Yamuna Ghats, Paonta Sahib (Himachal Pradesh, India) in September to October 2021. The species was authenticated at CSIR-IHBT, Palampur, and a voucher specimen (PLP#22087) was deposited. Samples were air-dried in shade, coarsely ground, 10 g of each was soaked for 24 hours at room temperature in 250 mL of methanol: distilled water (80:20). 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulphonic acid) diammonium salt (ABTS), hydrogen peroxide (H_2O_2), aluminium chloride ($AlCl_3$), potassium persulfate ($K_2S_2O_8$), 2,2-diphenyl-1-picrylhydrazyl (DPPH), free radical antioxidant powder (FRAP), 2,4,6-tripyridyl-s-triazin were used, with most chemicals sourced from Merck Limited (Mumbai, India) in analytical grade.

Antioxidant activity of *Physalis longifolia* extracts was evaluated through standard assays. Total phenolic content (TPC) and total flavonoid content (TFC) were measured using the Folin–Ciocalteu and aluminium chloride methods, respectively. Total antioxidant capacity (TAC) was assessed via the phospho-molybdenum assay. DPPH radical scavenging and FRAP assays were conducted to determine free radical inhibition and reducing power. Gallic acid, quercetin, ascorbic acid, and $FeSO_4$ were used as standards. Results were expressed in standard equivalents per gram of extract (Singla and Pradhan 2019, Banothu *et al.* 2017).

DPPH scavenging activity (%) = $[((A_{Control}-(A_{Sample}-A_{Sample\ blank}))/A_{Control}] \times 100$

GC-MS analysis was performed using a Shimadzu GC 2010 with an AOC-5000 auto-injector and SH-Rxi-5Sil MS column (30/ m × 0.25/ mm). The temperature was ramped from 40°C to 220°C, then held for 21 minutes. Samples in HPLC-grade dichloromethane were injected using helium (1.28/

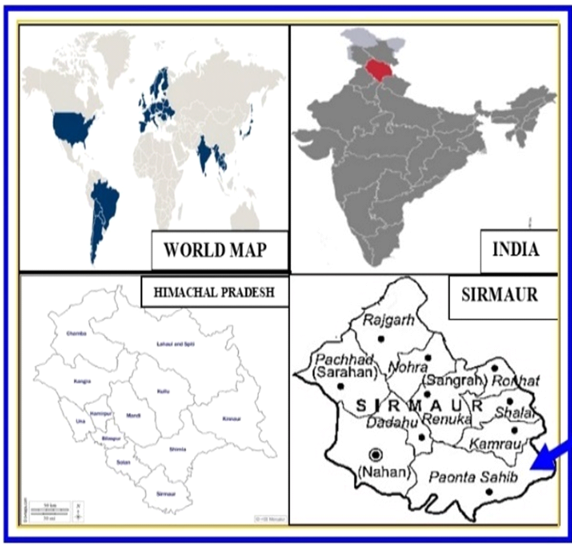

Figure 2. Map displaying the precise location of *Physalis longifolia* plant sample collection

(A) Plant **(B) Leaves** **(C) Berries**

Figure 1. *Physalis longifolia* in its native environment

mL/min, split 1:10) as the carrier gas. Components were identified via mass spectra comparisons with NIST and Wiley libraries. Chromatograms were generated for hydroalcoholic leaf and fruit extracts. Data were analysed using GraphPad Prism v7.01.

RESULTS AND DISCUSSION

Total phenolic (TPC) and flavonoid content (TFC) in *P. longifolia* were expressed as gallic acid and quercetin equivalents (mg/g DW). Leaf extracts showed higher TPC (27.5 mg GAE/g) and TFC (136.7 mg QE/g) than fruit extracts (TPC: 13.1 mg GAE/g; TFC: 80.48 mg QE/g). These compounds contribute to antioxidant activity by neutralizing free radicals via hydroxyl and methyl groups. Elevated phenolic levels in leaves are linked to environmental and stress-related factors. Flavonoids, the second most abundant phenolics in leaves, are concentrated in outer tissues and provide UV protection. Their accumulation, particularly of quercetin and kaempferol, increases with UV-B exposure, while fruit shading reduces flavonoid synthesis and gene expression, especially in skins. These trends align with prior studies on related species (Treutter 2005, Pillai *et al.* 2022, Nathiya and Dorcus 2012).

Leaf extracts exhibited higher total antioxidant capacity (29.4 ± 0.174 mg AAE/g DW) than fruit extracts (26.3 ± 0.105 mg AAE/g DW) (**Table 1**). DPPH assay results (**Figure 3**) demonstrated dose-dependent radical scavenging, with leaf extracts showing significantly greater inhibition (72.1 ± 1.14%) than fruits (45 ± 0.0964%) at 1000 µg/mL, along with lower IC_{50} values, indicating superior antioxidant potential. FRAP assay results also revealed concentration-dependent activity. While fruits showed slightly higher activity than leaves at 100 µg/mL, leaf extracts displayed lower IC_{50} values overall. At 1000 µg/mL, fruits reached 206 ± 1.00%, and leaves 145 ± 0.196%. These findings highlight

Table 1. Total phenolic, flavonoid, and antioxidant content of different plant parts of *Physalis longifolia*

Plant parts	TPC (mg GAE/g DW)	TFC (mg QE/g DW)	TAC (mg AA/g DW)
Leaves	27.5 ± 0.605	136.7 ± 2.034	29.4 ± 0.174
Fruits	13.1 ± 0.782	80.48 ± 0.238	26.3 ± 0.105

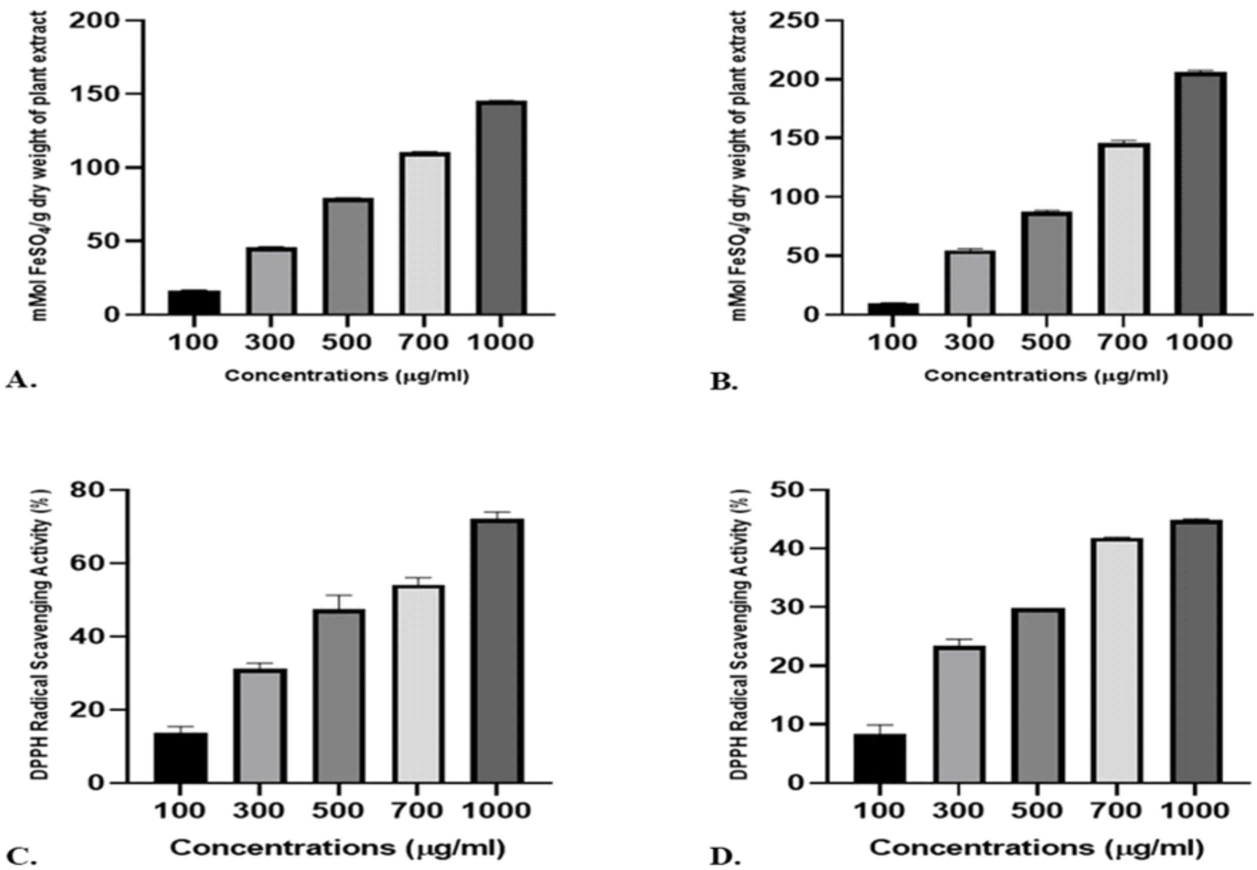

Figure 3. Antioxidant activities of hydroalcoholic extracts of *Physalis longifolia* leaves and fruits, *in vitro*. Data represent mean ± standard error (SE). (A) FRAP assay for leaf extract; (B) FRAP assay for fruit extract; (C) DPPH radical-scavenging leaf extract; and (D) DPPH radical-scavenging fruit extract

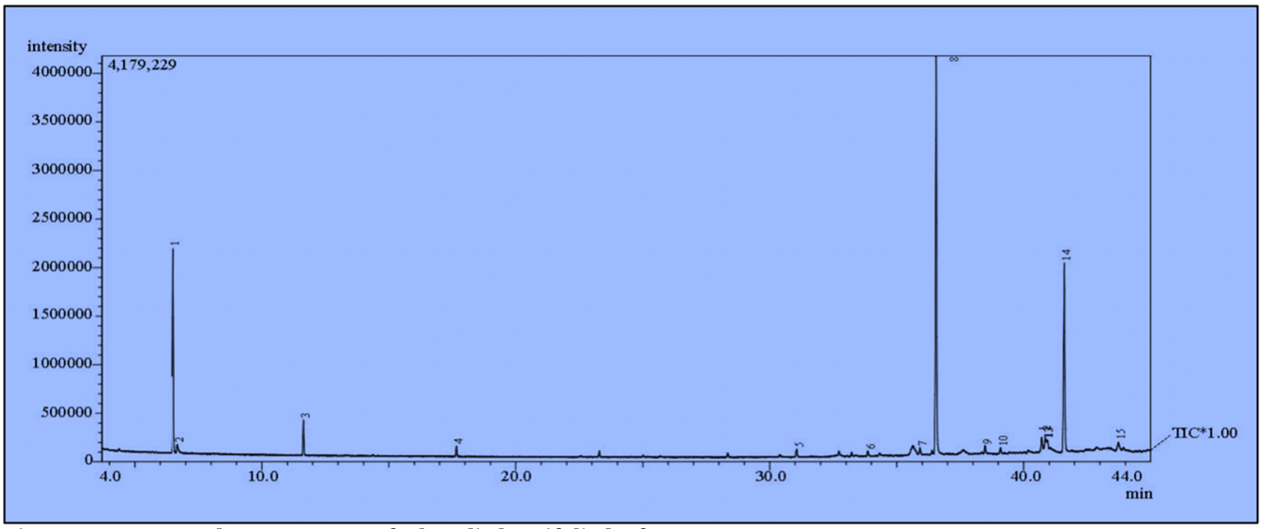

Figure 4. GC-MS Chromatogram of *Physalis longifolia* leaf extract

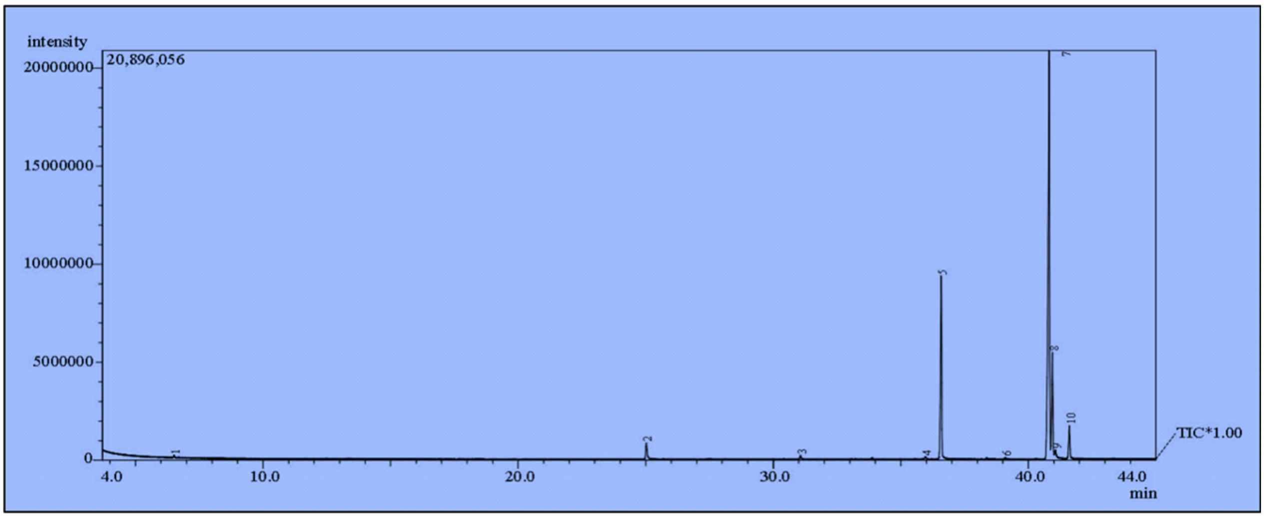

Figure 5. GC-MS Chromatogram of *Physalis longifolia* fruit extract

the strong antioxidant capacity of *P. longifolia* leaves and support further investigation into their bioactive constituents.

Previous research by Parikh *et al.* (2018) and Saeed *et al.* (2012a) demonstrated the use of total phenolic content (TPC), total flavonoid content (TFC), and total antioxidant capacity (TAC) as effective indicators of antioxidant potential in plants, underscoring their significance as natural sources of antioxidants. In this study, the antioxidant activity of two traditionally utilized parts of *Physalis longifolia* was assessed using FRAP and DPPH assays, which operate through distinct mechanisms—electron transfer in FRAP and both electron and hydrogen atom transfer in DPPH (Kýrca and Arslan 2008). The study revealed that leaf extracts contained higher TPC and TFC levels compared to fruits, which likely contributes to their greater antioxidant activity (Sroka and Cisowski 2003).

GC-MS analysis of *P. longifolia* leaf extract identified 15 bioactive compounds, notably Hexadecenoic acid methyl ester (43.52%), Methyl stearate (22.90%), and Cyclotetrasiloxane, octamethyl- (18.99%) (**Table 2**). The fruit extract revealed major constituents such as 9,12-Octadecadienoic acid methyl ester (59.89%) and Methyl palmitate (20.38%) (**Figure 5**). Both extracts exhibit diverse phytochemicals, including terpenes, fatty acids, and organosilicons, with potential medical and industrial applications.

Bioactive compounds like isoprenoids are recognized for their therapeutic benefits, including disease risk reduction. Terpenes, present in both plant parts, have uses in food, cosmetics, pharmaceuticals, and biofuels (Ponder and Hallmann 2019; Thimmappa *et al.* 2014). GC-MS analysis of *P. longifolia* leaves and fruits identified key bioactive compounds with therapeutic potential, including 9,12-octadecadienoic

Table 2. Chemical composition of methanolic-water fractions from *Physalis longifolia*

Compound	RT (min)		% Peak Area		MW	Molecular	Nature of the compound
	PLL	PLF	PLL	PLF	(g/mol)	Formula	
Cyclotetrasiloxane, octamethyl-	6.49	-	18.99	-	296.61	$C_8H_{24}O_4Si_4$	Organo-silicon
3-Oxo-Butyric Acid 2-Chloro-Ethyl Ester	6.67	-	1.00	-	86.17	C_6H_{14}	Long chain alkane
Cyclopentasiloxane, decamethyl-	11.64	-	3.22	-	370.77	$C_{10}H_{30}O_5Si_5$	Organo-silicon
Methane, dichloro- (CAS) Dichloromethane	-	6.51	-	0.19	84.93	CH_2Cl_2	Volatile organic compound
Dodecanoic acid, methyl ester (CAS) Methyl laurate	-	25.02	-	2.13	214.34	$C_{13}H_{26}O_2$	Saturated Fatty acid methyl ester
Cyclohexasiloxane, dodecamethyl	17.66	-	1.00	-	444.92	$C_{12}H_{36}O_6Si_6$	Organo-silicon
Heptadecanoic acid, methyl ester	31.05	39.10	0.89	0.18	284.48	$C_{18}H_{36}O_2$	Saturated Fatty acid ester
Tetra decanoic acid, methyl ester (CAS) Methyl myristate	-	31.07	-	0.39	242.40	$C_{15}H_{30}O_2$	Saturated Fatty acid ester
9-Hexadecenoic acid, methyl ester	-	35.96	-	0.22	270.45	$C_{17}H_{34}O_2$	Monounsaturated Fatty acid ester
Arachidic acid methyl ester (CAS) Eicosanoic acid	33.86	-	0.59	-	326.56	$C_{21}H_{42}O_2$	Monounsaturated Omega-9 Fatty acid ester
Pentacosane	35.91	-	0.71	-	352.68	$C_{25}H_{52}$	Aliphatic hydro-carbon
Hexadecanoic acid, methyl ester (CAS) Methyl palmitate	36.56	36.59	43.52	20.38	270.45	$C_{17}H_{34}O_2$	Monounsaturated Fatty acid ester
Triacontane	38.48	-	0.86	-	422.81	$C_{30}H_{62}$	Long chain alkane
Heptacosanoic acid, methyl ester	39.09	-	0.60	-	424.74	$C_{28}H_{56}O_2$	Saturated Fatty acid ester
9,12-Octadecadienoic acid (Z, Z)-, methyl ester	-	40.82	-	59.89	280.44	$C_{18}H_{32}O_2$	Polyunsaturated Omega-6 Fatty acid
9-Octadecanoic acid (Z)-, methyl ester	-	40.94	-	11.89	296.49	$C_{19}H_{36}O_2$	Monounsaturated Omega-9 Fatty acid ester
Hexadecadienoic acid, methyl ester	40.71	-	1.68	-	322.52	$C_{21}H_{38}O_2$	Saturated Fatty acid ester
8,11,14-Eicosatrienoic acid, methyl ester	40.86	-	1.95	-	320.51	$C_{21}H_{36}O_2$	Polyunsaturated Omega-6 Fatty acid ester
2-methyl tetracosane	43.73	-	1.14	-	352.68	$C_{25}H_{52}$	Tri- terpenoid
Methyl stearate	41.60	41.61	22.90	3.76	298.50	$C_{19}H_{38}O_2$	Saturated Fatty acid ester
Methyl oleate	-	41.06	-	0.96	296.49	$C_{19}H_{36}O_2$	Polyunsaturated Fatty acid

RI^a =calculated retention indices; RI^b =retention indices from literature; -: absent; % = relative percentages calculated from GC-FID

acid (Z, Z)-, hexadecanoic acid methyl ester, methyl stearate, and cyclotetrasiloxane octamethyl, also reported in traditional remedies (Ukwubile *et al.* 2019; Tulandi *et al.* 2021). Hexadecanoic acid methyl ester, found in both parts, exhibits antioxidant, anti-inflammatory, antimicrobial, and anticancer activities. 9,12-Octadecadienoic acid methyl ester demonstrates antioxidant, neuroprotective, and anti-COVID effects (Zayed *et al.* 2019). Methyl stearate and cyclotetrasiloxane octamethyl possess antibacterial properties and applications in food and cosmetics (Keskin et al. 2012). Minor constituents such as dodecanoic and Eicosatrienoic acid methyl esters contribute antioxidant, antifungal, and anti-allergic effects (**Table 2**). The dominant fruit compound, 9,12-octadecadienoic acid methyl ester, along with others, also exhibits hypocholesterolmic activity.

Conclusions

This study is the first, to our knowledge, in India to use GC-MS to profile metabolites in *Physalis longifolia*, and it identified 15 phytochemicals in leaves and 10 in fruits from methanolic-water extracts. It also links these compounds to antioxidant activity, highlighting their therapeutic potential. The findings support the *Physalis longifolia*'s traditional medicinal use and suggest that it may serve as a potential source for drug/medicines development or health supplements. However, limited research exists on its biological functions, underscoring the need for further studies to isolate compounds from various plant parts and assess their anticancer and other therapeutic properties.

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RESEARCH ARTICLE

Parasitic and non-parasitic weed flora in selected areas of the Indian Sundarbans

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ABSTRACT

A study was conducted to investigate the biodiversity and ecological roles of angiosperm plant parasites and weeds, focusing on parasitic and non-parasitic species in selected regions of the Indian Sundarbans. A total of four angiosperm parasites and eight weed species belonging to eight taxonomic families (Loranthaceae, Asclepiadaceae, Poaceae, Cyperaceae, Aizoaceae, Chenopodiaceae, Convolvulaceae and Amaranthaceae) were recorded from the study area. Plants of Loranthaceae and Asclepiadaceae have diverse host preferences. The infestation of parasitic angiosperms, *viz. Hoya parasitica, Viscum orientale, Viscum monoicum* and *Dendrophthoe falcata,* were primarily recorded in the canopies of specific host plants with a preference for *Xylocarpus granatum, Xylocarpus mekongensis, Heritiera fomes* and *Bruguiera* spp. in the intermediate and upper canopy zones; whereas, *Sonneratia apetala, Excoecaria agallocha,* and *Avicennia officinalis* were recorded as rarely infested mangrove species. *Porteresia coarctata* and *Cyperus malaccensis* were two important weeds in the mangrove ecosystem. Besides, *Sesuvium portulacastrum, Suaeda nudiflora, Salicornia brachiata, Sarcolobus carinatus, Heliotropium curassavicum,* and *Ipomoea pes-caprae* were also distributed widely in this region. The frequency, density, and abundance of parasitic and non-plastic weed flora in the study area were recorded to understand their habitat and impact on ecological equilibrium in the mangrove ecosystem.

Keywords: Biodiversity, Host-parasite interactions, Indian Sundarbans, Mangrove plants, Parasitic weeds, Weeds

INTRODUCTION

The Indian Sundarbans, a UNESCO (United Nations Educational, Scientific and Cultural Organization) World Heritage Site, is globally acknowledged for its significance and distinguished for its abundant biodiversity and distinctive mangrove ecology (Sarker *et al.* 2016). There exist the most extensive continuous mangrove forests, spanning over 10,000 square kilometers, and the Ganges, Brahmaputra, and Meghna rivers delta across India and Bangladesh (Mondal *et al.* 2012, Ghosh *et al.* 2015). The Sundarbans hosts 105 mangrove species, including true mangrove, mangrove associate, and angiospermic parasitic plants. Some of the important true mangrove plants in Sundarbans are Sundari (*Heritiera fomes*), Genwa (*Excoecaria agallocha*), Goran (*Ceriops decandra*) and Keora (*Sonneratia apetala*) (Rodriguez *et al.* 2012, Basak *et al.* 2015). Weeds are plants that grow where and when they are not desired, often competing with cultivated plants for light, water, and nutrients (Rathore 2014). Mangrove weeds denote undesirable plant species that infiltrate and proliferate in disrupted mangrove ecosystems, particularly in regions modified by human activities such as sand filling, dredging, or deforestation (Numbere 2020). These weeds may flourish in the distinctive circumstances of mangrove ecosystems, often characterized by salty and marshy soils (Chen 2019).

Angiospermic parasites and weeds directly affect the mangrove ecosystem. Both may affect native mangrove species, possibly decrease biodiversity and change the ecological equilibrium of the mangrove environment. Weeds may also alter the different physical and chemical properties of soil (Mongia *et al.* 2001). Several research findings indicate that some weed species may absorb pollutants from the soil, including heavy metals and hydrocarbons, functioning as bioremediation agents. This may mitigate soil pollution but also result in the buildup of deleterious compounds inside the weeds (Bashir *et al.* 2023). Weeds and parasites may serve as a home for several insect pests and diseases, potentially affecting the mangrove environment and adjacent human populations differently.

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Parasitic plants fulfill a portion of their nutritional needs by extracting resources from their host plants (Parker and Riches 1993). Various categories of parasites demonstrate unique adaptations and strategies for their parasitic lifestyle. They frequently trigger chlorophyll breakdown, rendering photosynthesis unfeasible (Shrestha 2012). They rely on their host plants for moisture, nourishment, and structural integrity. A unique structure, 'haustoria', infiltrates the tissue system of the host to get nutrients (Mallaburn 1992, Ghosh *et al.* 2004, Mathiasen *et al.* 2008). Certain angiospermic parasites depend on a single host plant, while others may infect several plants. Host specificity is dictated by physiological reliability, host availability, and environmental conditions (Bell and Adams 2011). Angiospermic plant parasites are fascinating and ecologically essential, demonstrating unique survival and reproduction strategies (Nickrent 2020). The genus *Loranthus* includes mistletoes, categorized as hemiparasitic plants that adhere to the branches of host trees and shrubs. Parasitic plants from the Scrophulariaceae family infiltrate the roots of adjacent plants to extract water and nutrients. Epiphytic bromeliads are often found in mangroves; nevertheless, their existence is frequently unrecorded in studies of mangrove vegetation (Sousa and Colpo 2017).

Certain angiosperm parasites and weeds may acclimate to the mangrove ecosystem while competing with indigenous plants for resources, exacerbating conservation challenges. An understanding of the parasites and weeds is essential for preserving the ecological integrity of the Sundarbans and sustaining local livelihoods. The present study was carried out to assess the biodiversity and ecological role of angiosperm plant parasites and non-parasitic weeds, to understand their habitat and impact on maintaining ecological equilibrium in the mangrove ecosystem of Indian Sundarbans.

MATERIALS AND METHODS

The Sundarbans is the most significant delta area globally, created by the confluence of three main rivers: the Ganges, Brahmaputra, and Meghna. The Indian Sundarbans, located next to the southern border of West Bengal, include a substantial area of the North 24 Parganas and South 24 Parganas districts. The current research was conducted in designated locations within the Indian Sundarbans area of the South 24-Parganas district in West Bengal (21°31'03"N – 22°30'03"N, 88°10'03"E – 89°51'03"E) from 2019 to 2022. The sample area included the administrative divisions of Basanti, Gosaba, and Kultali. The chosen locations display an abundance of halophytic plant species. The terrain dynamics of these locations lead to significant variations in their surface attributes.

A random region sample was collected by positioning 120 quadrats, each measuring 10 m x 10 m, from September 2019 to March 2022. Utilizing a slide caliper, we documented all trees inside each quadrat exhibiting a circumference/diameter at breast height (dbh) of ≥1cm, along with their quantities and dbh measurements. In instances when dbh measurement proved unfeasible, the girth at breast height (gbh) was ascertained using a measuring tape. Four quadrats measuring 2.5 m x 2.5 m were used to gather samples of shrubs, climbers, and tree seedlings of over 30 cm height. Four quadrats (1 m x 1 m), each situated inside a 10 m × 10 m quadrat, were used to gather samples of herbs, including tree seedlings measuring less than 30 cm in height. Frequency (F), density (DN), abundance (A), relative frequency (RF), relative density (RD) and relative abundance (RA) were obtained (Sreelekshmi *et al.* 2020) as follows:

$$\text{Frequency (F)} = \frac{\text{Number of quadrats of occurrence of a species} \times 100}{\text{Total number of quadrats studied}}$$

$$\text{Density (DN)} = \frac{\text{Total number of individuals of a species} \times 100}{\text{Total number of quadrats studied}}$$

$$\text{Abundance (A)} = \frac{\text{Number of individuals of a species} \times 100}{\text{Number of quadrats of occurrence of the species}}$$

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of species} \times 100}{\text{The sum of the frequency of all the species}}$$

$$\text{Relative density (RD)} = \frac{\text{Density of a species} \times 100}{\text{The sum of the density of all the species}}$$

$$\text{Relative abundance (RA)} = \frac{\text{Total number of individuals of a species in all quadrats} \times 100}{\text{Total abundance of all the species}}$$

The biodiversity indices were calculated to unveil the species richness, dominance, abundance, evenness and others important parameters (Sreelekshmi *et al.* 2020) by using the statistical analytical software PAST 4.03 and IBM SPSS 20. For each quadrat sample biodiversity data were quantified using several ecological indices. The Dominant Index (d) =" $(\frac{ni}{N})^2$, where ni is the number of individuals of species *i* and N is the total number of individuals, measures the dominance of a few species in a community (Simpson 1949). The Shannon-Wiener index [H' = $-\sum_{i=1}^{s} Pi \ln Pi$], Simpson's index [D= $\frac{1}{\sum_{i=1}^{s}(Pi)^2}$)], Pielou's Index for species evenness [J =$\frac{H'}{Log\ S}$] and Margalef's index of species richness [R = $\frac{(S-1)}{\log N}$] were calculated

(Shannon and Weaver 1949, Simpson 1949, Pielou 1966, Margalef 1968). Where s=total no of species, pi= ni/N, ni= total no of individuals of "i" species, N= total no of individuals of all species, ln= natural log. Where s=total no of species, pi= ni/N, ni= total no of individual of "i th" species, N= total no of individual of all species, ln= natural log.

Brillouin Index [$H_B = \frac{\ln(N!) - \sum \ln(ni!)}{N}$], is particularly suitable when the population is completely censused (Brillouin 2013). For richness, the Menhinick Index [$D_{Mn} = \frac{S}{\sqrt{N}}$], relates the number of species S to sample size (Menhinick 1964). The Fisher's Alpha Index [$S_{\acute{a}} = \alpha \ln\left(1 + \frac{N}{\alpha}\right)$ assumes a log-series distribution and is sensitive to rare species (Fisher *et al*. 1943). The Berger–Parker Index [$d_{BP} = \frac{Nmax}{N}$], where Nmax is the abundance of the most common species, measures dominance by the single most abundant species (Berger and Parker 1970). Finally, the Chao-1 Index [$S_{est} = (Sobs + \frac{(F1)2}{2F2})$], where Sobs is observed species richness, F_1 is the number of singletons, and F_2 is the number of doubletons, estimates true species richness by accounting for rare, undetected taxa (Chao 1984).

RESULTS AND DISCUSSION

Host selection and parasitism

In the Sundarbans, parasitic plants might select mangrove species based on their physiological compatibility, chemical signaling, and ecological interactions. Mistletoes (Loranthaceae) might have the potential to parasitize mangrove species that possess dense foliage and adequate nutrients, while they tend to overlook environments characterized by lower nutritional levels. Another species, *Viscum orientale* had the potential to parasitize specific mangrove species, such as *Heritiera fomes*, *Excoecaria agallocha* and *Bruguiera* spp. while *Viscum monoicum* was often found on *Bruguiera* spp. and *Xylocarpus* spp. The important member of Loranthaceae was *Dendrophthoe falcata*, has a broader variety of hosts than the previous ones, including *Xylocarpus* spp., *Excoecaria agallocha*, *Heritiera fomes*, and *Sonneratia apetala*. *Hoya parasitica* (Asclepiadaceae) associated with *Bruguiera* spp. and *Xylocarpus* spp. were found to contribute towards mangrove canopy structural and biological richness (**Table 1**).

Species composition

In the present study, twelve plant species identified were of the families *viz.* Loranthaceae, Asclepiadaceae, Poaceae, Cyperaceae, Aizoaceae, Amaranthaceae, Chenopodiaceae, and Convolvulaceae. Madur kathi, *Cyperus malaccensis* was the most common weed in density (93.33%), followed by another weed, Dhani Ghas, *Porteresia coarctata* (89.17%) and Giria Shak, *Suaeda nudiflora* (87.50%). *Cyperus malaccensis* had the higher abundance (2.74%), underscoring its status as a dominating species although *Porteresia coarctata* (2.25%) and *Heliotropium curassavicum* (2.33%) also had a significant presence. In contrast, species such as Mandala, *Viscum orientate* and Shamu lata, *Viscum monoicum* had lower abundance values, indicating that the angiospermic plant parasites invaded the Indian part of Sundarbans less rapidly than the two types of grasses. High relative frequencies of *Cyperus malaccensis* (21.37%) and *Porteresia coarctata* (20.42%) indicates that the mangrove area changed its habitat due to natural and anthropological effects. The lower relative density values *Viscum orientale* (6.19%) indicates that the lower density of this species might be due to specific

Table 1. Ecological analysis of parasitic and non-parasitic weed species in the Indian Sundarbans

Species	Family	F (%)	D (%)	A (%)	RF (%)	RD (%)	RA (%)	Host plants
Viscum orientate	Loranthaceae	60.83	0.43	0.70	13.93	6.19	8.10	*Bruguiera* spp., *Excoecaria agalloclia. Heritiera fomes*
Viscum monoicum	Loranthaceae	68.33	0.53	0.77	15.65	7.64	8.91	*Bruguiera* spp., *Xylocarpus* spp.
Dendrophthoe falcata	Loranthaceae	55.83	0.60	1.07	12.79	8.73	12.47	*Xylocarpus* spp., *Excoecaria agalloclia, Heritiera fomes, Sonneratia apetala*
Hoya parasitica	Asclepiadaceae	69.17	0.75	1.08	15.84	10.92	12.58	*Bruguiera* spp., *Xylocarpus* spp.
Porteresia coarctata	Poaceae	89.17	2.01	2.25	20.42	29.23	26.13	-
Cyperus malaccensis	Cyperaceae	93.33	2.56	2.74	21.37	37.24	31.80	-
Sesuvium portulacastrum	Aizoaceae	54.17	0.88	1.62	6.37	5.96	7.99	-
Suaeda nudiflora	Amaranthaceae	87.50	1.83	2.10	10.28	12.49	10.37	-
Salicornia brachiate	Amaranthaceae	80.83	1.06	1.31	9.50	7.21	6.48	-
Sarcolobus carinatus	Asclepiadaceae	73.33	1.12	1.52	8.62	7.61	7.53	-
Heliotropium curassavieum	Chenopodiaceae	73.33	1.71	2.33	8.62	11.64	11.53	-
Ipomoea pes-caprae	Convolvulaceae	45.00	1.23	2.72	5.29	8.34	13.47	-

A: abundance, D: density, F: frequency, RA: relative abundance, RD: relative density, RF: relative frequency ecological circumstances or host availability **(Table 1)**. The prevalence of *Cyperus malaccensis* and *Porteresia coarctata* indicated their adaptation to the local environment, possibly owing to their tolerance of soil composition, moisture levels, and sunshine exposure. Semi-parasitic species from the Loranthaceae family, including *Viscum orientale*, *Viscum monoicum*, and Himelata, *Dendrophthoe falcata*, exhibited intermediate frequency and density, indicating a specialized niche reliant on host trees rather than direct competition for terrestrial space (**Figure 1**). These plants could enhance ecological diversity and provide resources for wildlife in their environment. Positive effects of plants belonging to Loranthaceae on forest environment were studied by Burgess *et al.* (2006). Salt-tolerant plants such as *Suaeda nudiflora* and Baro Lonia, *Salicornia brachiata* are crucial to mangroves ecosystem due to their facilitating soil stability and enhancing nutrient cycling. Chagalkuri, *Ipomoea pes-caprae* and *Heliotropium curassavicum* exhibited limited abundance. *Ipomoea pes-carpae* is well-improved in sandy soils, where it helps in erosion prevention and stabilizes banks (Kaufman *et al.* 2015). The trend line (or regression line) fitted to the data points indicated a positive correlation between abundance and relative density. The equation of the trend line is y=5.406x”0.76789 suggesting that as abundance increases, relative density also tends to increase (**Figure 2)** as observed by Kaufman *et al.* (2015). The positive slope of the trend line implies that species with higher abundance also have higher relative density values, indicating a strong relationship between these two variables in this ecosystem. The

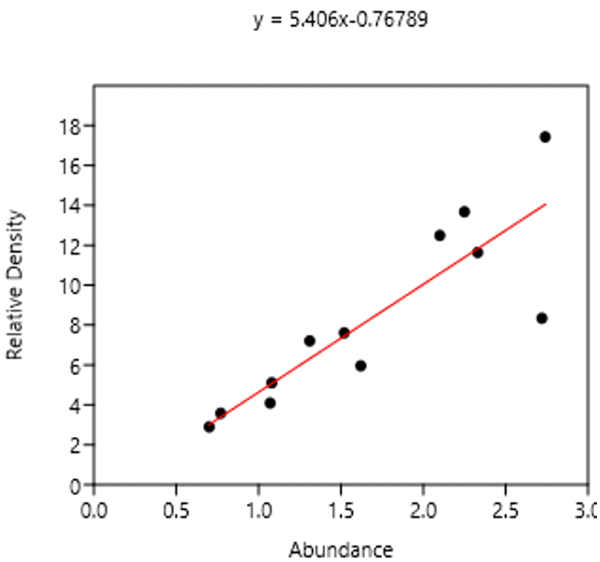

Figure 2. Correlation between relative density and abundance of plant species in the Sundarbans mangrove ecosystem

study emphasized the need to conserve true and mangrove-associated species within the region.

Species diversity and community structure

The Indian Sundarbans exhibited a comprehensive species richness, distribution, and ecosystem structure within this crucial mangrove area. A total of twelve species were identified, comprising 1,615 individuals, indicative of a diverse ecosystem with a well-balanced species composition. The Dominance Index (d) of 0.12 indicates low dominance within the community structure, implying that no single species significantly overshadows the area (**Table 2**).

The Simpson Index (1-D) of 0.88 reflects a significant level of biodiversity coupled with minimal dominance (Chakraborty *et al.* 2009). The Simpson Index of 1, as noted in this study, indicates significant diversity (Sreelekshmi *el al.* 2020). The Shannon Index (H) of 2.25 reinforces the moderate to high diversity, as higher Shannon Index is generally associated with species richness and evenness. As the Shannon Index considers the abundance and distribution of each species the Shannon Index (H) of 2.25 indicates that the sampled species are diverse and represented in balanced quantities, fostering a robust ecological background (**Table 2**).

The Evenness Index (e^H/S) of 0.86 and the Equitability_J Index of 0.94 indicate a balanced distribution among the species. The Brillouin Index (2.23) considers species abundance and arrangement, closely matching Shannon’s diversity outcome and confirming that the community exhibits diversity and even distribution. The Menhinick Index (0.27) and Margalef Index (1.35) are metrics for assessing species richness and sample size. The Fisher’s Alpha Index (1.59) introduces an additional layer to this diversity evaluation, indicating

Table 2. Biodiversity indices of the vegetation sampled in the Indian Sundarbans

Number/Indices	Values
Number of the species identified	12.00
Total number of individuals	1615.00
Dominance Index (d)	0.12
Simpson index (1-D)	0.88
Shannon Index (H)	2.25
Evenness Index (e^H/S)	0.86
Brillouin index	2.23
Menhinick index	0.27
Margalef index	1.35
Equitability_J index	0.94
Fisher_alpha index	1.59
Berger-Parker index	0.19
Chao-1 index	12.00

a moderate degree of richness and the existence of less common species within the sample (Satheeshkumar and Khan 2012). The Berger-Parker Index (0.19) reinforces the notion of low dominance among the vegetation species, indicating a well-balanced biodiversity where no single species prevails over the others. This equilibrium illustrates the collaborative framework within mangrove ecosystems, where species frequently utilize resources collectively to enhance the ecosystem's enduring health (**Table 2**).

Species richness

The Chao-1 Index (12) estimates species richness while considering the possibility of undetected species and closely corresponds with the observed species count. This indicates that the sample effectively represents the species present in the area. The indices together illustrate a multifaceted and harmonious ecosystem, showcasing significant species diversity, minimal dominance, and fair distribution among species in the Indian Sundarbans (Das *et al.* 2022).

Furthermore, the significance of high diversity and evenness is especially pronounced in the Sundarbans, where distinctive species interactions - like those involving salt-tolerant plants, sediment-binding roots, and specialized fauna - constitute the basis of a cohesive ecosystem. The low dominance level coupled with high evenness indicates that a diverse array of plants contributes to ecological services, thereby bolstering the stability of the ecosystem. The rich biodiversity is vital in enhancing local ecological health while bolstering global conservation initiatives. The Sundarbans are essential as a significant carbon sink, a sanctuary for rare and endangered species, and a protective shield for coastal communities.

A proliferation of the parasite on branches, especially in clusters, is the most definitive sign of infestation in mangrove trees. Impacted mangroves may show poorer growth and health, indicated by markedly smaller leaves and a general decline in condition. Physiological stress associated with nutritional deficiencies caused by the parasite's resource depletion is most frequently demonstrated as chlorosis or curling leaf symptoms. If the branches have a significant amount of infection, the whole branches can die back, and if not taken care of, the tree can die back, too. Also, Loranthus' spread would hamper sunlight from reaching the leaves of the mangrove and such would reduce photosynthesis and further endanger the decline of the plant. Due to their importance in the sustainable management and preservation of mangrove ecosystems, timely identification of indicators is of primary importance. The strategies for effective management of parasites are necessary to mitigate their impacts and preserve the health of mangrove ecosystems.

Conclusion

The Indian Sundarbans is a unique and critical mangrove environment for coastal stability as well as rare and endangered species. The observed parasitic and non-parasitic weed flora influence the biodiversity of Sundarbans mangroves significantly. They help to maintain the diversity of ecology and adaptability but uncontrolled spread can cause the extinction of native mangrove species. Thus, in order to maintain the ecological balance and the long-term stability of Sundarbans mangrove ecosystem, ecological-checks on the major weeds and the parasitic angiosperms and the control thereof need to be monitored in an opportune manner. Protecting this World Heritage Site is essential, thus protecting regional biodiversity and environmental stability.

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RESEARCH NOTE

Evaluation of a few herbicides efficacy alone and in combination for controlling weeds in fodder oats grown for seed production

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ABSTRACT

A field study was conducted during *Rabi*, 2023-24 at Forage Research Block of APRI, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar to evaluate the efficacy of few herbicides alone and in combination for weeds management in fodder oats seed production. Eleven treatments were tested on silty loam soils using RBD, replicated thrice. The tested treatments were: pre-emergence application (PE) of pendimethalin at 750 g/ha; oxyfluorfen at 200 g/ha PE; post-emergence application (PoE) of metsulfuron-methyl at 4 g/ha; 2,4-D at 500 g/ha PoE; pendimethalin at 750 g/ha PE followed by (*fb*) metsulfuron-methyl at 4 g/ha PoE; oxyfluorfen at 200 g/ha PE *fb* metsulfuron-methyl at 4 g/ha PoE; pendimethalin at 750 g/ha PE *fb* 2,4-D at 500 g/ha PoE; oxyfluorfen at 200 g/ha PE *fb* 2,4-D PoE at 500 g/ha; manual weeding twice at 20 and 40 days after seeding (DAS), hand hoeing at 20 DAS and weedy check. The *Cynodon dactylon* density was maximum with 38% relative density amongst the infested weed flora. The manual weeding twice at 20 and 40 DAS recorded the lowest weeds density and biomass and the highest fodder oats seed yield. Among the herbicides, pendimethalin at 750 g/ha PE *fb* metsulfuron-methyl at 4 g/ha PoE reduced the weed density and biomass and recorded the highest weed control efficiency, lowest weed index, highest nutrient uptake and crude protein yield and oats seed yield. The treatment oxyfluorfen at 200 g/ha PE *fb* metsulfuron-methyl at 4 g/ha PoE recorded the highest fodder oats straw yield.

Keywords: Fodder oats, Metsulfuron-methyl, Oxyfluorfen, Pendimethalin, Weed management

Fodder oats (*Avena sativa* L.), is one of the promising *Rabi* fodder crop offering high-quality forage used as livestock feed. Weeds deplete valuable soil nutrients and weed competition significantly limits fodder oats yield and quality. Weed infestations can reduce green forage yield by up to 31.4% (Singh *et al*. 2020). Effective weed management is therefore crucial to reducing competition and enhancing productivity. Effective weed management reduces yield losses, ensuring a reliable and abundant forage harvest. Uncontrolled weed growth, by contrast, can result in greater yield losses and lower-quality forage, which can be more costly over time. Although manual weeding and hoeing can effectively manage weeds in fodder oats production, these methods are often labour-intensive and costly. Due to labour shortages, particularly during critical growth periods, manual weeding and hoeing are often impractical, making chemical control an effective alternative. Thus, herbicides usage remains one of the most common and effective methods of weed management.

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Herbicide use is generally more cost-effective than mechanical or manual methods, with the most economical approach combining herbicides with manual weeding. The efficacy of herbicides, however, varies with factors such as weed species, growth stage and timing of application *etc*. In some cases, herbicides combinations broaden the spectrum of control, targeting multiple weed species. Furthermore, meeting specific purity and quality standards is necessary for certification and market access and weed management plays a critical role in meeting these standards. In seed production, the presence of weed seeds in the final product can lead to rejection or reduced marketability, making weed management essential to maintaining quality standards.

Oats are highly susceptible to diverse weed species, including broad-leaved weeds such as *Cichorium intybus*, *Chenopodium murale*, *Euphorbia hirta*, *Althaea ludwigii* and *Tribulus terrestris*, as well as narrow-leaved weeds like *Cyperus rotundus* and *Cynodon dactylon* (Singh *et al*. 2001). Weed control in forage crops is often overlooked since many farmers consider weeds as supplemental animal feed. Herbicides are central to modern weed management, enabling efficient control over large areas with lower labour requirements. Studies indicate that using a combination of different herbicides can yield higher productivity than single-herbicide applications (Kadam *et al.* 2021). This study was conducted with an objective to identify best weed management options for keeping oats fields weed-free, optimizing both fodder yield and seed quality and maximizing productivity in fodder oats seed production.

The field experiment on weed management in fodder oats seed production was conducted at Forage Research Block of APRI, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar with silty clay loam soil. The eleven treatments comprised of: pre-emergence application (PE) of pendimethalin at 750 g/ha, oxyfluorfen at 200 g/ha PE, post-emergence application (PoE) of metsulfuron-methyl at 4 g/ha, 2,4-D at 500 g/ha PoE, pendimethalin at 750 g/ha PE followed by (*fb*) metsulfuron-methyl at 4 g/ha PoE, oxyfluorfen at 200 g/ha PE *fb* metsulfuron-methyl at 4 g/ha PoE, pendimethalin at 750 g/ha PE *fb* 2,4-D at 500 g/ha PoE, oxyfluorfen at 200 g/ha PE *fb* 2,4-D (PoE) at 500 g/ha, manual weeding twice at 20 and 40 days after seeding (DAS), hand hoeing at 20 DAS and weedy check. A randomized block design replicated thrice was used. Oats cv. JHO-822 was sown on 7th December 2023 at a spacing of 25 cm row to row by using seed rate 100 kg/ha and was harvested on 6th April 2024. The crop was fertilized with recommended rate 120-60-40 kg NPK per hectare. Nitrogen was applied in two splits 60 kg N/ha as basal application and 60 kg N/ha at active tillering stage in the form of urea. Other agronomical and plant protection measures followed as per recommendation during the crop growth. Pre-emergence herbicides were sprayed 3 days after sowing on moist soil and post-emergence herbicides were sprayed at 20 DAS. Herbicides were sprayed according to the treatment by using knapsack sprayer in 500 litres of water/ha. Quadrat (0.5 m^2) was randomly placed at two places in each plot to count density and dry weight of weeds (weed biomass) at 30, 45 and 60 DAS and at harvest. Seed and straw yield (kg/ha) were also recorded at harvest. Data recorded during the experimental period was statistically analysed as per the standard procedure and weed data transformed by square root transformation $\sqrt{x+0.5}$ and transformed data were subjected to ANOVA analysis (Gomez and Gomez 1984).

Weed infestation in the experimental field

Eleven weed species, consisting of two grass, one sedge and eight broad-leaved weeds were observed in the research field during the crop growth period. *Cynodon dactylon*, *Cyperus rotundus*, *Cannabis sativa*, *Cirsium arvense*, *Anagallis arvensis*, *Polypogon monspeliensis*, *Oxalis corniculata*, *Chenopodium album*, *Parthenium hysterophorus, Scoparia dulcis* and *Physalis minima* were the dominant weeds (**Figure 1**).

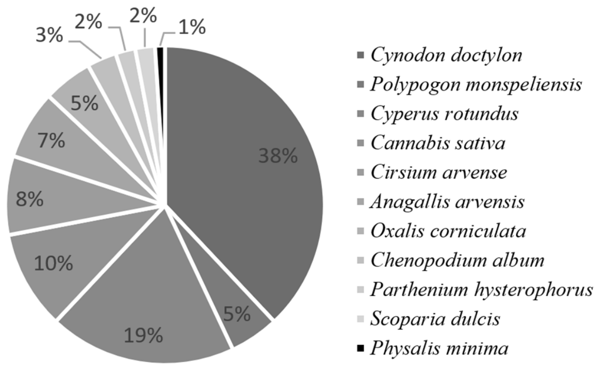

Figure 1. Relative dominance of weeds in experimental field

Weed density and biomass

Among the treatments evaluated, manual weed removal at 20 and 40 days after sowing (DAS) proved most effective in reducing weed density and biomass (**Table 1**). However, manual weeding results were statistically similar to those obtained with pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE due to suppression of grasses during initial weed growth stages by pendimethalin and then control of broad-leaved weeds (BLWs) by metsulfuron-methyl 4 g/ha PoE. The weedy check recorded the highest weed density and biomass due to the absence of weed control measures. Among the herbicides tested, metsulfuron methyl at 4 g/ha PoE effectively suppressed broad-leaved weeds, particularly *Cirsium arvense*, which remained unaffected by other herbicides. The combination of pendimethalin at 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE significantly reduced overall weed density (83.8%) and weed biomass (89.1%) compared to the weedy check at 60 DAS. Metsulfuron-methyl achieved 100% control of *Cirsium arvense*, while pendimethalin at 750 g/ha was most effective against *Chenopodium album* and showed effectiveness against *Anagallis arvensis* (Chopra *et al.* 2001). Furthermore, metsulfuron-methyl's residual effect was shown to last for over two months (Bhattacharya *et al.* 2006). Metsulfuron-methyl alone or in combination with 2,4-D Na was observed to offer excellent control of broad-leaved weeds in wheat (Pandey *et al.* 2012). Compared to 2,4-D, metsulfuron-methyl provided superior control of broad-leaved species (Singh and Ali 2004). The

Table 1. Efficacy of weed management treatments on weed density (no./m²), weed biomass (g/m²), weed control efficiency (WCE) and weed index (WI) in fodder oats crop grown for seed production

Treatment	Weed density				Weed biomass				WCE	WI
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	60 DAS	At harvest
Pendimethalin 750 g/ha PE	2.96 (8.3)	2.58 (6.33)	4.73 (22.00)	6.08 (36.7)	1.19 (0.9)	1.12 (0.8)	1.71 (2.4)	2.14 (4.1)	80.28	20.50
Oxyfluorfen 200 g/ha PE	4.64 (21.0)	2.68 (6.7)	3.13 (9.3)	6.12 (37.0)	1.66 (2.3)	1.15 (0.8)	1.28 (1.1)	2.17 (4.2)	79.71	23.36
Metsulfuron-methyl 4 g/ha PoE	4.38 (18.7)	2.55 (6.0)	2.67 (6.7)	5.64 (31.3)	1.53 (1.8)	1.10 (0.7)	1.13 (0.8)	1.96 (3.3)	83.88	8.54
2,4-D 500 g/ha PoE	4.41 (19.0)	2.61 (6.3)	2.91 (8.0)	5.82 (33.3)	1.65 (2.2)	1.14 (0.8)	1.25 (1.1)	2.14 (4.1)	80.29	16.73
Pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE	2.85 (7.7)	2.61 (6.3)	2.54 (6.0)	4.52 (20.0)	1.18 (0.9)	1.08 (0.7)	1.09 (0.7)	1.66 (2.3)	89.17	2.69
Oxyfluorfen 200 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE	3.94 (15.0)	2.67 (6.7)	2.60 (6.3)	5.34 (28.3)	1.50 (1.7)	1.09 (0.7)	1.12 (0.7)	1.92 (3.2)	84.73	12.69
Pendimethalin 750 g/ha PE *fb* 2,4-D 500 g/ha PoE	2.90 (8.0)	2.61 (6.3)	2.86 (7.7)	4.74 (22.0)	1.19 (0.9)	1.10 (0.73	1.23 (1.0)	1.77 (2.7)	87.26	10.79
Oxyfluorfen 200 g/ha PE *fb* 2,4-D 500 g/ha PoE	3.85 (14.3)	2.54 (6.0)	2.80 (7.3)	5.31 (27.7)	1.41 (1.5)	1.12 (0.8)	1.18 (0.9)	1.91 (3.1)	84.90	9.21
Manual weeding twice at 20 and 40 DAS	2.72 (7.0)	2.47 (5.7)	2.48 (5.7)	4.32 (18.3)	1.07 (0.6)	1.03 (0.6)	1.06 (0.6)	1.52 (1.8)	91.27	0.00
Hand hoeing once at 20 DAS	3.12 (9.3)	2.59 (6.3)	3.67 (13.0)	5.38 (28.7)	1.38 (1.4)	1.13 (0.8)	1.57 (2.0)	2.16 (4.2)	79.90	18.37
Weedy check	6.92 (47.3)	3.98 (15.3)	7.84 (61.0)	11.14 (123.7)	2.90 (8.0)	1.75 (2.6)	3.28 (10.3)	4.62 (20.8)	0.00	31.91
LSD (p=0.05)	0.32	0.39	0.34	0.41	0.13	0.13	0.12	0.17	-	-

DAS = days after seeding; PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by; BLWs: broad-leaved weeds

highest weed control efficiency (WCE) was recorded with manual weeding twice 20 and 40 DAS. Among herbicidal treatments, pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE recorded the highest WCE, due to reductions in both weed density and biomass. The WCE of pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE was 89.2% at 60 DAS and recorded weed index with it was 2.69 at harvest. These findings are in close agreement with the findings of Pisal and Sagarka (2013), Bhattacharya *et al.* (2006), Sharma and Chander (2006), Singh *et al.* (2019), Barikzai and Thalkar (2021) and Shubhashree *et al.* (2023).

Fodder oats yield, nutrient uptake and crude protein

The highest fodder oats seed yield was achieved with manual weeding twice at 20 and 40 DAS, which was statistically comparable to pendimethalin 750 g/ ha PE *fb* metsulfuron-methyl 4 g/ha PoE (**Table 2**). These methods provided a 46.9% and 43.1% increase in seed yield, respectively, compared to the weedy plot. The highest straw yield was achieved with oxyfluorfen 200 g/ha PE *fb* metsulfuron-methyl 4 g/ ha PoE, however, it was comparable to manual weeding twice at 20 and 40 DAS and pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE. Similar findings were reported by Pisal and Sagarka (2013) and Bhattacharya *et al.* (2006).

The weedy check treatment had the lowest uptake of nitrogen, phosphorus and potassium, whereas the manual weeding twice at 20 and 40 DAS resulted in the highest uptake of these nutrients. Among the herbicidal treatments pendimethalin 750 g/ ha PE *fb* metsulfuron-methyl 4 g/ha PoE recorded the highest N, P and K uptake. Pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE improved total N, P and K uptake by 60.6%, 93.9% and 44.7%, respectively, compared to the weedy check. These findings are supported by studies conducted by Singh and Saha (2001) and Pisal and Sagarka (2013).

The lowest crude protein yield in both seed and straw were found in weedy check. In contrast, the highest crude protein content and yield were recorded in the treatment with manual weeding twice at 20 and 40 DAS, which was comparable to the pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE. The application of pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE significantly boosted crude protein yield, increasing it by 70% in seed and 54.3% in straw compared to the weedy check. Similar findings were reported by Singh *et al.* (2020).

Table 2. Fodder oats yield, crude protein yield and nutrient uptake as influenced by weed management strategies in fodder oats grown for seed production

Treatment	Seed yield (t/ha)	Straw yield (t/ha)	Nitrogen			Phosphorous			Potassium			Crude protein yield (kg/ha)	
			Seed	Straw	Total	Seed	Straw	Total	Seed	Straw	Total	Seed	Straw
Pendimethalin 750 g/ha PE	3.04	7.85	39.48	65.93	105.41	5.37	6.51	11.88	10.48	120.03	130.51	247	412
Oxyfluorfen 200 g/ha PE	2.93	7.82	37.76	64.91	102.67	5.10	6.21	11.31	9.75	117.51	127.25	236	406
Metsulfuron-methyl 4 g/ha PoE	3.49	8.08	47.95	75.20	123.15	7.05	7.14	14.19	13.08	124.84	137.92	300	470
2,4-D 500 g/ha PoE	3.18	8.23	43.26	70.59	113.85	5.66	7.04	12.70	11.74	125.70	137.45	270	441
Pendimethalin 750 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE	3.72	8.57	55.18	86.29	141.47	7.99	8.13	16.12	14.48	141.45	155.93	345	539
Oxyfluorfen 200 g/ha PE *fb* metsulfuron-methyl 4 g/ha PoE	3.34	8.95	46.21	82.64	128.86	6.63	8.00	14.63	11.71	146.01	157.72	289	517
Pendimethalin 750 g/ha PE *fb* 2,4-D 500 g/ha PoE	3.41	8.12	46.28	74.60	120.88	6.94	7.29	14.23	12.76	133.08	145.84	289	466
Oxyfluorfen 200 g/ha PE *fb* 2,4-D 500 g/ha PoE	3.46	8.33	50.58	75.07	125.65	7.08	6.90	13.98	12.37	127.28	139.65	316	469
Manual weeding twice at 20 and 40 DAS	3.82	8.76	59.39	94.42	153.82	8.81	9.71	18.52	15.27	161.27	176.54	371	590
Hand hoeing once at 20 DAS	3.12	7.38	42.02	69.18	111.20	6.17	6.30	12.47	11.43	118.34	129.77	262	432
Weedy check	2.60	7.25	32.42	55.70	88.11	3.97	4.34	8.31	8.04	99.69	107.73	203	348
LSD (p=0.05)	0.29	0.98	5.43	9.08	12.88	0.58	0.97	1.39	1.52	14.42	15.06	31	55

* PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by

Conclusion

It may be concluded that pendimethalin at 750 g/ha PE *fb* metsulfuron-methyl at 4 g/ha PoE may be used for weed management in fodder oats grown for seed production as it recorded the lowest weed density and biomass at all the growth stages with highest weed control efficiency and lowest weed index; highest fodder oats nutrient uptake and crude protein yield and seed yield.

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RESEARCH NOTE

Saflufenacil to manage weeds in soybean

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ABSTRACT

This study was conducted at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh (U.P.) during the *Kharif* season of 2023-24. The aim was to evaluate the efficacy of saflufenacil against weeds in soybean (*Glycine max* L.). A randomized block design (RBD) was used with seven treatments, *viz.* four dosage rates of saflufenacil at 16, 22, 25, and 50 g/ha, diclosulam 26 g/ha, hand weeding twice at 20 and 40 days after sowing (DAS), and unweeded check, replicated thrice. Hand weeding at 20 and 40 DAS resulted in maximum weed control, growth of soybean and highest seed yield, amongst the tested treatments. Saflufenacil 50 g/ha caused the lowest weed density, weed biomass, and highest weed control efficiency which improved soybean growth parameters, yield-related characteristics and increased yield of soybean amongst saflufenacil dosage rates tested.

Keywords: Diclosulam, Herbicides, Soybean, Saflufenacil, Weed management

Effective weed management is crucial to minimize weed competition and optimize soybean growth and production. Despite advanced technologies, producers often report high losses due to weeds. The estimated potential soybean yield loss was 50-76% due to weed infestation (Gharde *et al.* 2018). In order to reduce yield losses due to weeds in soybean production, efficient and strategic weed management practices are the fundamental need.

Saflufenacil, a pre-emergent herbicide with protoporphyrinogen oxidase (PPO) mode of action, has demonstrated broad-spectrum efficacy against both annual and perennial weeds, including species resistant to conventional herbicides (Grossmann *et al*. 2010). It is absorbed by both the roots and foliage of plants, primarily transported through the xylem, with limited movement in the phloem (Soltani *et al.* 2012). Its quick action, broad weed control spectrum, and favorable environmental profile make it a promising option for soybean growers struggling with diverse weed populations (Liebl *et al*. 2008). It can be applied as both pre- and post-emergence and is also found to be effective in controlling glyphosate resistance horseweed (*Conyza* sp.) (Mellendorf *et al.* 2013). However, limited studies have been conducted to evaluate its efficacy in controlling specific weed species such as *Cynodon dactylon*, *Cyperus rotundus*, and *Parthenium hysterophorus* which are dominant in soybean field under Indian agro-climatic conditions. Hence, an experiment was conducted to assess the efficacy of saflufenacil to manage weeds in soybean.

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The study was conducted at the Agricultural Research Farm of the Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh. A randomized block design (RBD) was used with seven treatments replicated thrice. The treatments include: saflufenacil at four dosage rates, *viz.* 16, 22, 25 and 50 g/ha, diclosulam 26 g/ha, hand weeding twice at 20 and 40 days after sowing (DAS) and unweeded check. Soybean variety RVSM 2011-35 was sown on 23rd June 2023 in a 7×3 m sized plot each. Herbicides were applied as pre-emergence application (PE) at 3 days after sowing (DAS) by using knapsack sprayer fitted with flat fan nozzle. The weed density was recorded at 30, and 60 days after treatment application (DAT) by placing 1 × 1m quadrat at three random places per plot. Additionally, weed biomass was recorded at 30, and 60 DAT by uprooting weeds, followed by hot air drying at 70°C and weighing. Weed control efficiency (WCE), herbicide efficiency index (HEI) and weed management index (WMI) was computed using the equation suggested by Mani *et al.* (1973) and Mishra and Misra (1997).

Crop and weed data were subjected to analysis of variance (ANOVA) for RBD as given by Gomez and Gomez (1984). Weed density and weed biomass data was square root transformed ($\sqrt{x+0.5}$). Post-hoc analysis using Duncan's multiple range test (DMRT) was performed using Statistical Tool for Agricultural Research (STAR), IRRI, version 2.0.1. The same software was used for correlation analysis.

Weed flora

Weed flora in the experimental area consisted of grasses: *Cynodon dactylon* L., *Echinochloa colona* L.

and *Paspalum conjugatum* P.J. Bergius; sedges: *Cyperus rotundus* L. and *Cyperus esculents* L.; broad-leaved weeds: *Parthenium hysterophorus* L., *Phyllanthus niruri* L., *Eclipta alba* L., *Ludwigia parviflora* and *Lindernia procumbens*. The predominant weed flora in experimental field were *Cyperus rotundus* accounting (58%), *C. esculentus* (8%), *C. dactylon* (7%), *P. hysterophorus* (9%) and *Phyllanthus niruri* (5% of the total weeds).

Effect on weeds

Saflufenacil at all dosage rates significantly reduced the weed density of different weed *species* compared to the weedy check (**Table 1**). The lowest weed density, biomass and highest weed control efficiency (WCE) among herbicidal treatments tested was recorded with saflufenacil 50 g/ha. The hand weeding recorded the lowest weed biomass of grasses, sedges and broad-leaved weeds (**Table 2**). Although the highest WCE (84.97%) was under hand weeding twice at 20 and 40 DAS, the application of saflufenacil recorded equally higher WCE (**Table 2**). This might be due to the efficacy of saflufenacil as a pre-emergence herbicide and its ability to control a broad spectrum of broad-leaved weeds (Mueller *et al.* 2014). Moreover, saflufenacil has residual activity (half-life of 59 days under saturated condition and 33 days under field capacity) that provides extended control of weed species over time (Camargo *et al.* 2013). This residual effect helped in maintaining lower weed densities throughout the critical periods (15-45 DAS) of soybean growth (Kumar *et al.* 2022; Liebl *et al.* 2008).

Interestingly, diclosulam 26 g/ha exhibited the highest HEI (1.26), indicating its effectiveness in enhancing soybean yield per unit of weed biomass reduction. This finding aligns with findings of Gulaiya *et al.* (2023) who reported that diclosulam provides excellent residual control of broad-leaved weeds and is particularly effective in soybean. Saflufenacil 25 and 50 g/ha both recorded the highest values (0.74) of weed management index. The high WMI values for saflufenacil treatments indicate that these doses effectively balanced weed control with crop productivity.

Table 1. Weed density as influenced by weed control treatments in soybean

Treatment	Weed density (no./m^2)					
	Total sedges		Total grasses		Total broad-leaved weeds	
	30 DAT	60 DAT	30 DAT	60 DAT	30 DAT	60 DAT
Saflufenacil 16 g/ha	17.45(304.3)	20.83(434.0)	7.31(53.3)	9.80(96.0)	2.01(4.0)	6.91(47.7)
Saflufenacil 22 g/ha	14.88(221.3)	17.07(291.3)	6.98(48.7)	9.11(83.0)	1.55(2.3)	6.29(39.6)
Saflufenacil 25 g/ha	12.32(151.7)	14.90(222.0)	6.61(43.6)	8.27(68.3)	0.22(0)	5.27(27.7)
Saflufenacil 50 g/ha	11.46(131.3)	13.93(194.0)	6.28(39.3)	8.09(65.3)	0.22(0)	4.81(23.0)
Diclosulam 26 g/ha	16.27(264.7)	19.43(377.3)	7.22(52.0)	9.47(89.7)	2.01(4.0)	6.63(43.9)
Hand weeding twice at 20 and 40 DAS	4.03(16.2)	13.84(191.6)	3.47(12.0)	5.18(26.8)	0.22(0)	3.08(9.4)
unweeded check	21.16(447.7)	23.83(567.6)	8.15(66.3)	10.39(108.0)	8.27(68.3)	11.31(127.9)
LSD (p=0.05)	1.53	2.01	1.02	1.28	0.72	1.45

Original figures in parentheses were subjected to square-root transformation ($\sqrt{x+0.5}$) before statistical analysis. DAS- days after seeding; DAT-days after treatment application

Table 2. Weed biomass and weed indices (60 DAT) as influenced by weed control treatments in soybean

Treatment	Weed biomass (g/m^2)*								WCE (%)	HEI	WMI
	Sedges		Grasses		Broad-leaved		Total				
	30 DAT	60 DAT	30 DAT	60 DAT	30 DAT	60 DAT	30 DAT	60 DAT			
Saflufenacil 16 g/ha	8.93 (79.3)	9.58 (91.30)	3.97 (15.27)	5.89 (34.20)	0.90 (0.31)	2.57 (6.09)	9.77 (94.88)	11.49 (131.59)	58.25	0.53	0.49
Saflufenacil 22 g/ha	7.55 (56.5)	9.29 (85.90)	3.66 (12.91)	5.23 (26.90)	0.83 (0.19)	2.39 (5.23)	8.37 (69.0)	10.88 (118.03)	62.56	0.76	0.64
Saflufenacil 25 g/ha	6.68 (44.14)	8.85 (77.97)	3.48 (11.64)	4.52 (19.98)	0.80 (0.14)	2.10 (3.93)	7.51 (55.92)	10.11 (101.88)	67.68	0.81	0.74
Saflufenacil 50 g/ha	6.23 (38.35)	8.15 (65.98)	3.30 (10.38)	4.27 (17.75)	0.79 (0.12)	2.01 (3.55)	7.02 (48.85)	9.36 (87.28)	72.31	1.04	0.74
Diclosulam 26 g/ha	7.96 (62.93)	9.45 (88.98)	3.85 (14.32)	5.56 (30.36)	0.88 (0.28)	2.49 (5.72)	8.83 (77.53)	11.20 (125.06)	60.33	1.26	0.58
Hand weeding twice at 20 and 40 DAS	1.97 (3.4)	6.37 (40.12)	1.65 (2.3)	2.52 (5.9)	0.71 (0)	1.36 (1.35)	2.48 (5.7)	6.91 (47.37)	84.97	-	0.71
Unweeded check	10.28 (105.19)	13.90 (192.59)	4.39 (18.81)	9.29 (85.94)	2.27 (4.66)	6.09 (36.75)	11.36 (128.66)	17.76 (315.22)	-	-	-
LSD (p=0.05)	0.56	0.80	0.27	0.39	0.08	0.20	0.45	0.54			

*Original figures in parentheses were subjected to square-root transformation ($\sqrt{x+0.5}$) before statistical analysis; WCE- Weed control efficiency; HEI – Herbicide efficiency index; WMI – Weed management index; DAS- days after seeding; DAT-days after treatment application

Table 3. Soybean growth and yield attributes as influenced by weed control treatments

Treatment	Crop biomass (g/m^2)		Pods/ plant	100-seed weight (g)	Seed yield (kg/ha)	Stover yield (kg/ha)	Harvest index (%)
	30 DAT	60 DAT					
Saflufenacil 16 g/ha	85.03	217.68	32.67	9.7	1283	2181	37.04
Saflufenacil 22 g/ha	89.38	229.71	34.33	9.9	1401	2288	37.98
Saflufenacil 25 g/ha	95.49	246.36	36.33	10.3	1504	2356	38.96
Saflufenacil 50 g/ha	95.87	247.44	36.87	10.5	1538	2384	39.21
Diclosulam 26 g/ha	87.12	223.03	33.00	9.8	1353	2216	37.91
Hand weeding twice at 20 and 40 DAS	98.89	253.16	37.33	10.8	1605	2487	39.22
Unweeded check	64.72	165.68	27.67	8.9	998	1894	34.51
LSD (p=0.05)	3.61	7.01	1.40	0.51	70.5	115	1.17

*DAS- days after seeding; DAT-days after treatment application

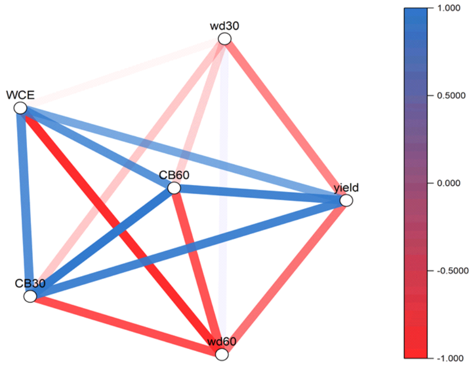

Figure 1. Correlation between various parameters under study. Wd30- weed density at 30 DAT; wd60- weed density at 60 DAT; CB30- crop biomass at 30 DAT; CB60- crop biomass at 60 DAT; WCE- weed control efficiency

Soybean growth and yield attributes

Hand weeding twice at 20 and 40 DAS resulted in the highest crop biomass, pod count, and seed yield (**Table 3**), signifying the effectiveness of manual weed control, though it may be labor-intensive (Richard *et* al. 2023). Among the tested herbicides, saflufenacil 50 g/ha produced the highest crop biomass at 30 DAT and 60 DAT, seed yield, stover yield and harvest index. Similar observations were made by Walsh *et al.* (2015).

Correlation analysis

Higher weed biomass at 30 and 60 DAT are strongly negatively correlated with WCE, crop biomass at 30 and 60 DAT and seed yield (**Figure 1**), indicating greater weed competition for resources, which lead to lower soybean growth and yield. Additionally, there is strong positive correlation in WCE with crop biomass at 30 and 60 DAT and soybean seed yield.

Conclusion

Saflufenacil 50 g/ha effectively managed weeds in soybean resulting in substantial increases in soybean biomass and yield. Hence, saflufenacil 50 g/ ha is recommended for adequate weed management and soybean productivity.

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RESEARCH NOTE

Weeds as potential reservoirs and hosts for root-knot nematodes in tomato cultivation

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ABSTRACT

Tomato, the most widely cultivated vegetables globally, is significantly threatened by biotic factors, particularly root-knot nematodes (RKNs) like *Meloidogyne* species, which are polyphagous parasites with a broad host range. Weeds play a crucial role as alternative hosts for RKNs, enabling their persistence in fields and serving as reservoirs of infection for subsequent crops. This study focuses on the Kolar district of Karnataka, India, a major tomato-producing region, where prominent weed hosts of RKNs are identified which include *Mesosphaerum suaveolens*, *Crassocephalum crepidioides, Spermacoce ocymoides, Portulaca oleracea*, *Solanum nigrum, Alternanthera sessilis, Ageratum conyzoides* and *Emilia sonchifolia* showing symptoms of nematode infection, such as gall formation. Morphological identification of nematode species revealed the presence of *Meloidogyne incognita*, *M. javanica,* and *M. enterolobii*. The findings underscore the importance of managing weed populations to control nematode infestations and mitigate their impact on tomato cultivation.

Keywords: *Meloidogyne* spp., Tomato, Root-knot nematodes, Reservoirs, Weed hosts

Tomato is the most widely grown vegetable in the world and global tomato production reached 41.52 million tonnes by 2020 and is projected to rise to approximately 51.93 million tonnes by 2026, as per the prevailing worldwide forecast (Chandrasekaran *et al*. 2021). Karnataka is one among the primary tomato-producing states in India which along with other states contribute to approximately 90% of the country's total tomato production (NHB 2019). Among the array of biotic constraints affecting tomato production, root-knot nematodes (RKNs) are among the important ones and cannot be overlooked.

While often perceived as nuisances due to their competitive nature and ability to reduce crop yields, weeds also serve as crucial collateral hosts for various plant pathogens, including nematodes (Lopez *et al*. 2021). RKNs have the ability to persist on weeds regardless of whether there is a main host present in the field, thereby serving as a reservoir of infection for subsequent crops and heightening the risk of disease (Rich *et al*. 2008). Even after the primary crop is harvested, these weeds retain nematodes, maintaining their presence in the soil and perpetuating a continual threat to future crops.

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Root-knot nematodes, in particular, exhibit a polyphagous nature with a broad host range that enables them to infect numerous plant species. These undesirable plants provide breeding ground for nematodes, particularly root-knot nematodes, which are obligate parasites relying on living plant hosts for survival and reproduction. The presence of weeds complicates nematode management efforts, as eradication becomes more challenging once nematodes establish populations in weed reservoirs (Schwarz *et al*. 2024). It is believed that weeds result in more significant crop losses compared to pathogens or insects individually (Fried *et al*. 2017). When coupled with nematodes in the field, their combined effect could pose a more significant threat to crop production (Dentika *et al*. 2021). Kolar, located in Karnataka, India, is renowned for its significant contribution to tomato production. RKNs that infect tomato plants may find alternative hosts in weed plants that proliferate in the inter-cropping phase, potentially serving as reservoirs until the next crop is planted. It is therefore important to identify the weed hosts of nematode to mitigate their impact on tomato crops.

A survey and sampling were conducted from February to March (2023) in tomato fields located in five different areas within Kolar district, Karnataka, to identify weeds serving as hosts for RKNs. This study was carried out during the period between the removal of the previous tomato crop and the planting of a new vegetable crop. The primary objective was to identify and assess common weed hosts of RKN present in the fields during this intermediate period. Initially, common weed species growing in the tomato fields were catalogued. While looking for weed hosts of nematodes, the focus was particularly on those weed plants that were found growing in the planting holes of black plastic mulch, previously used for tomato cultivation, as these sites were more likely to harbour root-knot nematodes inoculum. Uprooted weeds were examined for symptoms of nematode infection, such as gall formation.

The collected weed samples were carefully labelled and transported to the AICRP-Nematodes laboratory at University of Agricultural Sciences, Bangalore, for further analysis. In the laboratory, the shoot portions of the weeds were separated from the roots. The roots were thoroughly washed with tap water to remove any adhering soil and debris. Clean roots were cut into 5-6 cm segments for further processing. Root segments were stained with acid fuchsin to enhance the visibility of nematodes (Bybd *et al.* 1983). After staining, the roots were preserved in a lactophenol solution to prevent decay and facilitate further examination. Female nematodes were carefully excised from the stained root samples.

Figure 1. Prominent weed hosts of root-knot nematodes. (a) ***Solanum nigrum*** **(black nightshade) (b)** ***Crassocephalum crepidioides*** **(Cressleaf groundsel) (c)** ***Portulaca oleracea*** **(Purslane) (d)** ***Mesosphaerum suaveolens*** **(Pignut) (e)** ***Alternanthera sessilis*** **(Sessile joyweed) (f)** ***Ageratum conyzoides*** **(Billygoat weed) (g)** ***Emilia sonchifolia*** **(Purple snow thistle) (h)** ***Spermacoce ocymoides*** **(Button weed)**

Their perineal patterns were observed under a compound microscope to identify and classify the different species of RKNs present.

In the tomato fields of Kolar, Karnataka, prominent identified weeds were: *Bidens pilosa* (Beggar's tick), *Euphorbia hirta* (Asthma weed), *Emilia sonchifolia* (Purple snow thistle), *Amaranthus viridis* (Green Amaranth), *Portulaca oleracea* (Purslane), *Cleome viscosa* (Tickweed), *Solanum nigrum* (Black nightshade), *Ageratum conyzoides* (Billygoat weed), *Chenopodium album* (Lamb's quarters), *Crassocephalum crepidioides* (Cressleaf groundsel), *Cyperus rotundus* (Nutgrass), *Mesosphaerum suaveolens* (Pignut), *Commelina benghalensis* (Benghal dayflower), *Spermacoce ocymoides* (Button weed), *Convolvulus arvensis* (Field bindweed), *Sporobolus indicus* (Smutgrass), *Digitaria sanguinalis* (Crabgrass), *Alternanthera sessilis* (Sessile joyweed), *Mimosa pudica* (Sensitive plant). Among these common weeds, we observed gall formation as shown in the **Figure 1**, which is a typical symptom of RKNs on eight weeds (**Table 1**). Among which three weeds belonged to *Asteraceae* family, one belonged to the family *Solanaceae* and others belonged to *Lamiaceae*, *Rubiaceae*, *Portulacaceae* and *Amaranthaceae* family. Tomato plants that were found growing as volunteer crops from the seeds of the previous season crop were also found infected with RKNs.

The nematode count per 5g of root samples varied across the identified weed hosts. Among the prominent weeds, *Solanum nigrum* recorded the highest nematode density with 490 ± 14 (Mean ± SE) individuals, followed by *Mesosphaerum suaveolens* with 380 ± 15 and *Crassocephalum crepidioides* with 325 ± 12. *Ageratum conyzoides* had a similar infestation level, showing 330 ± 13 nematodes per 5g of roots. *Portulaca oleracea* exhibited 285 ± 18,

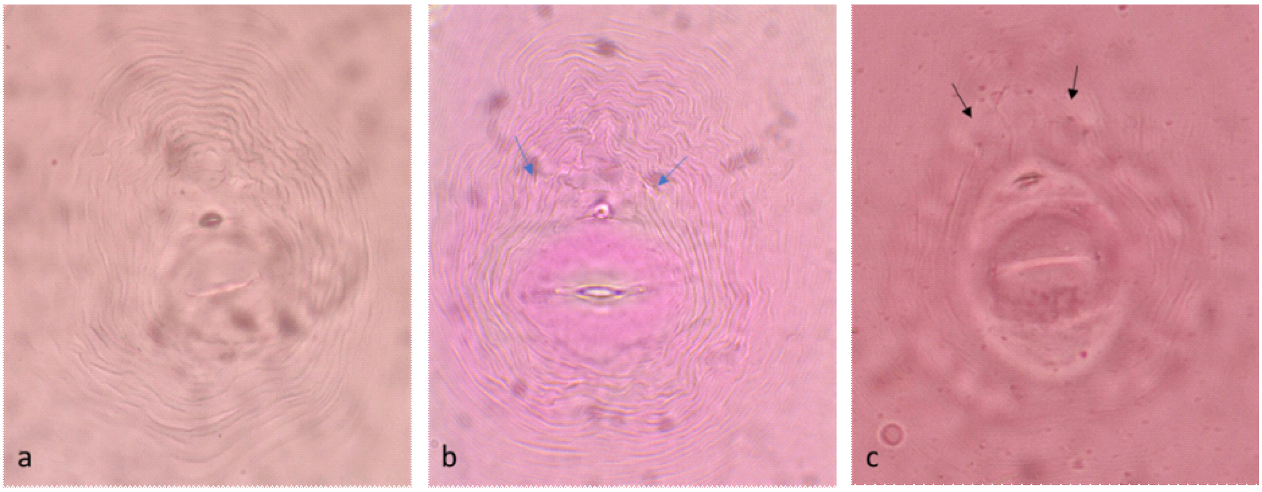

Figure 2. Perineal pattern of RKN species (a) *Meloidogyne incognita*, (b) *M. javanica* and (c) *M. enterolobii*. (Blue arrows indicate lateral lines and black arrows indicate phasmids)

Table 1. The prominent weeds that were identified as hosts of RKN at five different locations

Prominent weeds as reservoirs of RKN	Family	Location				
		A1	A2	A3	A4	A5
Mesosphaerum suaveolens	*Lamiaceae*	+	+	+	+	+
Crassocephalum crepidioides	*Asteraceae*	+	+	-	+	+
Spermacoce ocymoides	*Rubiaceae*	+	-	+	+	+
Portulaca oleracea	*Portulacaceae*	+	+	+	+	+
Solanum nigrum	*Solanaceae*	+		+	+	+
Alternanthera sessilis	*Amaranthaceae*	+	-	+	-	+
Ageratum conyzoides	*Asteraceae*	+	+	+	+	+
Emilia sonchifolia	*Asteraceae*	+	+	+	-	+
RKN species		*M. i, M. e, M. j*	*M. i*	*M. i, M. e*	*M. i*	*M. i, M. e*

A1- Talagavara, A2- Mathikunte, A3- Kumbiganahalli, A4- Kuduvanahlli, A5- Kolar
M. i- *Meloidogyne incognita*, M. e- *Meloidogyne enterolobii*, M. j- *Meloidogyne javanica*

while *Emilia sonchifolia* had 275 ± 10. Lower nematode counts were observed in *Spermacoce ocymoides* (210 ± 10) and *Alternanthera sessilis* (195 ± 11), indicating potential differences in susceptibility or nematode preference across weed species. These findings emphasize the role of diverse weed species in sustaining root-knot nematode populations, potentially contributing to their persistence in tomato fields.

Novel weed hosts

Among the eight weeds which were identified as prominent reservoirs of root-knot nematode, *Alternanthera sessilis, Crassocephalum crepidioides, Mesosphaerum suaveolen* and *Spermacoce ocymoides* stand out as particularly noteworthy. To the best of our knowledge, these weed species have not yet been reported as hosts for root-knot nematodes. This discovery highlights the potential role these weeds may play in the epidemiology of root-knot nematode infestations, underscoring the importance of further research to understand their impact on tomato cultivation.

Morphological identification of RKN species

Morphological identification of RKN species through morphological/external pattern identified three different species of RKN such as *M. incognita*, *M. javanica* and *M. enterolobii* (**Figure 2**). *M. incognita* typically showed a high, smooth and rounded dorsal arch with coarse, wavy striations. Whereas, *M. javanica* had a lower, flatter dorsal arch with finer, more parallel striations and distinct lateral lines. Perineal pattern of *M. enterolobii* resembled *M. incognita* with a high dorsal arch but featured more irregular and coarse striations, particularly in the dorsal region with prominent phasmids

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RESEARCH NOTE

Evaluation of weed management practices on growth and fruit yield of pomegranate (*Punica granatum* L.)

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ABSTRACT

A field experiment was carried with an objective to evaluate different weed management treatments and identify weed management treatments that effectively manages weeds and increases the growth and fruit yield of pomegranate (*Punica granatum* L.**)**. It was conducted at Central Block, Horticultural College and Research Institute, Periyakulam, Tamil Nadu during *Kharif* and *rabi* seasons of the years 2017-2018 and 2018-2019. Tested pre- and post-emergence herbicides in pomegranate were applied before the onset of South West monsoon and North East monsoon in *Kharif* and *Rabi* seasons respectively. Pre-emergence application (PE) of indaziflam 500 SC (indaziflam) 62.5 g/ha recorded significantly lower weeds density and biomass at 90 days after herbicide application (DAA) during both the seasons. Higher weed density was recorded in untreated control at all stages of crop growth during both the seasons. Indaziflam 62.5 g/ha recorded significantly lower weed biomass at 90 DAA. Next in effectiveness to manage weeds was indaziflam 50 g /ha during both the seasons and it resulted in higher weed control efficiency at all stages. There was no phytotoxicity due to indaziflam on pomegranate. Significantly higher pomegranate fruit yield was recorded with hand weeding during both *Kharif* and *Rabi* seasons and it was closely followed by indaziflam 62.5 g/ha. Indaziflam 62.5 g/ha recorded significantly higher fruit yield than the standard check of oxyfluorfen 940 g/ha during both the seasons.

Keywords: Fruit yield, Indaziflam, Oxyfluorfen, Pomegranate, Weed management,

One of the first known edible fruits, the pomegranate (*Punica granatum* L.) can grow in a variety of agro- climates, from tropical to temperate, across the globe. India accounts for half of global pomegranate production. Maharashtra leads the Indian states in terms of pomegranate production and area followed by Karnataka, Andhra Pradesh, and Gujarat. Due to its wonderful combination, sweet-acidic taste, and great dessert quality, it is a popular commercial fruit preferred by consumers worldwide. The fruit's edible portion is rich in essential minerals, polysaccharides, sugars, vitamins, acids, and polyphenols. Fruit juice's flavour is determined by the concentration of organic acids (citric, malic, oxalic, and succinic). The fruit is also well-liked because of its nutritional value and therapeutic qualities, which can be used to treat a variety of human disorders, including coronary heart disease, cancer (skin, breast, prostate, and colon), inflammation, hyperlipidaemia, diabetes, cardiac disorders, hypoxia, ischemia, aging, and brain disorders. Due to its broad adaptability, greater yield, drought resistance, and salinity tolerance, this crop is becoming more and more popular in arid and semiarid regions of India (Kaulgud 2002).

Weeds caused reduction in yield was noticed in agricultural and horticultural crops due to competition for the resources and also weeds served as alternate host for insects, diseases, nematodes and increased the pest problem. As pomegranate trees have fewer roots per unit of soil than weeds, fruit trees are considered to be weaker competitors. In order to prevent unregulated weed growth from competing with fruit trees for moisture and nutrients and interfering with orchard operations, lowering yields and raising production costs, timely weed control is essential. Herbicide application maintained bare soil between 0.6 and 2.0 m along the tree row has be found simple, economical, and beneficial for fruit production and tree growth (Harrington *et al*. 2005, Lisek 2014). Adequate weed control techniques are crucial to reduce weed competition and increase fruit production. Thus, an experiment was conducted with an objective to evaluate different weed management treatments and identify weed management treatments that effectively manages weeds and increases the growth and yield of pomegranate (variety Bhagwa).

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Experiment was conducted during *Kharif* and *Rabi* seasons of the 2017-2018 and 2018-2019 at Central Block, Horticultural College and Research Institute, Periyakulam, Tamil Nadu located at 10.13^0 N, 77.59^0 E and at an altitude of 289 m above mean sea level with average rainfall 791.1 mm. The soil was sandy loam having pH 7.1, organic carbon (0.28%), medium in available nitrogen (295 kg/ha), low in available P (10.6 kg/ha) and medium in available potash (228 kg/ha). A Randomized Block Design with three replications was used. The experiment consisted of ten treatments, *viz.* untreated control; indaziflam 500 SC (indaziflam) 37.5 g/ha, indaziflam 50 g/ha, indaziflam 62.5 g/ha, oxyfluorfen 23.5% EC (oxyfluorfen) 940 g/ha, weed free check with need based hand weedings, indaziflam 62.5 g/ha + glyphosate 41% SL (indaziflam + glyphosate) 1230 g/ha, indaziflam 62.5 g/ha + glufosinate-ammonium 13.5 % SL (indaziflam + glufosinate-ammonium) 500 g/ha, glyphosate 1230 g/ha and glufosinate-ammonium 500 g/ha. Indaziflam is an aliphatic group of herbicides.

The study was initiated in an already established pomegranate fields after pruning. Spacing of followed for pomegranate was 2.5 m x 3.0 m. Fertilizer dose of 0.60: 0.50: 1.2 kg/tree NPK was followed. Plant protection chemicals were applied as and when required. Other regular package of practices was followed in pomegranate as per TNAU Crop Production Guide.

Prior to the start of the monsoon, early-emerging weeds were manually removed. Pre-emergence application of indaziflam at different concentration was sprayed at the onset of South - West monsoon and North East monsoon periods. To keep the area weed-free, periodic hand weeding was followed. When the weeds were in the fourth to sixth leaf stages, post-emergence application of indaziflam was sprayed, as per the treatment, using a knapsack sprayer in a water volume of 500 L/ha. Weed density and weed biomass was recorded at 90 days after herbicide application (DAA) using standard procedures. Weed control efficiency was computed at 90 DAA. Data pertaining to weed density and biomass was subjected to square root transformation before statistical analysis. Statistical analysis was done as per the method suggested by Gomez and Gomez 1984).

The weed flora in the experimental field during the study period consisted of grasses and broad-leaved weeds. Sedges were not noticed in the experimental field. *Cynodon dactylon* and *Dactyloctenium aegyptium* among grasses and *Corchorus trilocularis, Acalypha indica, Boerhavia diffusa, Cleome viscosa, Eclipta alba, Euphorbia hirta, Leucas aspera, Phyllanthus niruri, Sida acuta* and *Trianthema portulacastrum* among major broad-leaved weeds were observed. *Cleome viscosa* and *Cynodon dactylon* were the dominant weeds.

Table 1. Effect of indaziflam on pomegranate fruit yield, weed density, weed biomass, weed control efficiency at 90 days after herbicide application

Treatment	Weed density (no./m²)						Weed biomass (g/m²)		Weed control efficiency (%)		Fruit yield (t/ha)	
	Kharif			*Rabi*								
	Grass	BLW	Total	Grass	BLW	Total	*Kharif*	*Rabi*	*Kharif*	*Rabi*	*Kharif*	*Rabi*
Untreated control	6.45 (41.5)	12.27 (150.5)	13.86 (192.1)	6.60 (43.6)	12.77 (163.1)	14.37 (206.70)	12.11 (146.6)	13.11 (171.8)	-	-	4.32	4.89
Indaziflam 37.5 g/ha PE	3.58 (12.8)	6.95 (48.3)	7.82 (61.1)	3.67 (13.5)	7.12 (50.7)	8.01 (64.2)	6.98 (48.7)	8.75 (76.6)	61.81	63.41	9.23	9.69
Indaziflam 50 g/ha PE	3.20 (10.2)	5.37 (28.9)	6.25 (39.1)	3.28 (10.7)	5.50 (30.3)	6.40 (41.0)	5.69 (32.4)	6.06 (36.7)	77.92	78.62	10.87	11.41
Indaziflam 62.5 g/ha PE	2.96 (8.8)	5.20 (27.1)	5.99 (35.8)	3.04 (9.2)	5.33 (28.4)	6.13 (37.6)	5.40 (29.1)	5.51 (30.4)	80.13	80.76	11.05	11.60
Oxyfluorfen 940 g/ha PE	3.51 (12.3)	6.84 (46.9)	7.69 (59.1)	3.59 (12.9)	7.01 (49.2)	7.88 (62.1)	7.69 (59.2)	8.44 (71.2)	59.62	60.89	9.68	10.16
Weed free check (hand weeding)	0.71 (0.5)	0.71 (0.5)	1.00 (1)	0.72 (0.5)	0.72 (0.5)	1.02 (1.1)	0.71 (0.5)	3.11 (9.7)	99.66	99.67	12.37	12.99
Indaziflam 62.5 g/ha + glyphosate 1230 g/ha PoE	3.57 (12.7)	6.52 (42.5)	7.43 (55.3)	3.66 (13.4)	6.68 (44.7)	7.62 (58.0)	7.76 (60.2)	7.99 (63.8)	58.95	60.24	10.18	10.69
Indaziflam 62.5 g/ha + glufosinate-ammonium 500 g/ha PoE	3.59 (12.9)	5.93 (35.2)	6.93 (48.1)	3.68 (13.6)	6.08 (36.9)	7.10 (50.5)	6.06 (36.7)	6.62 (43.9)	74.97	75.76	9.76	10.25
Glyphosate 1230 g/ha PoE	3.51 (12.3)	8.12 (65.9)	8.84 (78.2)	3.59 (12.9)	8.32 (69.2)	9.06 (82.1)	8.96 (80.2)	9.43 (89)	45.25	46.98	8.21	8.62
Glufosinate-ammonium 500 g/ha PoE	3.47 (12)	7.95 (63.1)	8.67 (75.2)	3.55 (12.6)	8.14 (66.3)	8.88 (78.9)	8.52 (72.6)	8.94 (79.9)	50.47	52.03	8.56	8.99
LSD (p=0.05)	0.087	0.115	0.183	0.089	0.141	0.171	0.148	2.031	-	-	0.321	0.533

Data in parentheses are original values which were subjected to square root transformation $\sqrt{x+0.5}$ before analysis; PE =pre-emergence application; PoE = post-emergence application

Effect on weeds

Significantly lower weed density was found in weed free check due to regular need-based hand weeding. Weeds were efficiently controlled by indaziflam PE applied alone or in combination with other post-emergence applied herbicides **(Table 1)**. Indaziflam 62.5 g/ha PE reduced the overall weed density considerably at all stages of observation followed by indaziflam 50 g /ha and indaziflam 62.5 g /ha + glufosinate-ammonium 500 g/ha during both the seasons of the study. **(Table 1).** These results are in conformity with the findings of Kavitha *et al*. (2021) in acid lime. Highest weed density was recorded in untreated control at all stages of crop growth during both the seasons.

Indaziflam 62.5 g/ha PE recorded significantly lower weed biomass at 90 DAA during both *Kharif* and *Rabi* seasons. It was superior to indaziflam 50 g/ ha. Weed biomass was more in untreated control, as expected, due to higher weed density. Weed control efficiency (WCE) was the highest in weed free check during both of the seasons. Indaziflam 62.5 g/ha recorded WCE of 80.13 and 80.76% at 90 DAA respectively during *Kharif* and *Rabi* seasons **(Table 1).** Lower weed density and biomass were associated with higher weed control efficiency (Patel *et al*. 2004).

Effect on pomegranate fruit yield

Weed free check produced a significantly higher fruit yield during both *Kharif* and *Rabi* season **(Table 1).** Indaziflam 62.5 g/ha PE resulted in significant increase in fruit yield. This treatment of 14.1% and 14.2% increase in fruit yield during *Kharif* and *Rabi* seasons, respectively as compared to the standard check of oxyfluorfen 940 g/ha. The unweeded control had the lowest yield. These results are in agreement with those of Patel *et al.* (2004).

Conclusion

Indaziflam 62.5 g/ha PE gave effective weed management and significantly higher pomegranate fruit yield than standard check oxyfluorfen 940 g/ha.

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RESEARCH NOTE

Utilization of calico plant (*Alternanthera bettzickiana (Regel)* Voss. as bio-organic manure through vermicomposting

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ABSTRACT

Calico plant (*Alternanthera bettzickiana (Regel)* Voss., an invasive weed, is now a major weed in different upland crops and waste lands in Kerala, India. The studies were conducted on vermicomposting of *A. bettzickiana* mixed with and without banana pseudostem in various proportions (v/v) (8:1, 4:1, 2:1, 1:1 and weed alone) along with cow dung. There was an increase in electrical conductivity and total contents of macronutrients (N, P and K) and micronutrients (Fe, Zn and Cu) along with a decrease in pH, total organic carbon (TOC) and C/N ratio after vermicomposting. Use of weed biomass alone and in combination with pseudostem (8:1) had significantly higher N, P content and earthworm growth and lower TOC and C/N ratio. Treatments with higher proportion of pseudostem produced compost with higher TOC, C/N ratio and K content. Compost recovery to the extent of 47 and 45.3% was observed in vermi-reactors with weed alone and mixed material (8:1), respectively, along with a lower rate of recovery (34%) in uniformly mixed proportion of weed + pseudostem (1:1). Increase in nutrient content and growth of earthworms in all the vermi-reactors indicated the suitability of *A. bettzickiana* for vermicomposting, which might be an effective way of utilizing the invasive weed biomass as bio-organic manure.

Keywords: *Alternanthera bettzickiana*, Banana pseudostem, bio-organic manure, Earthworm, *Eisenia fetida*, Vermicomposting, Weed utilization

Alternanthera bettzickiana (Regel) Voss., commonly known as calico plant, is an invasive weed species belonging to Amaranthaceae family. It is a native of tropical America, and is now distributed throughout the plains, degraded deciduous forests and wastelands in the southern and north-eastern states of India. Currently, it has been appearing as a major weed in vegetables, plantation crops, fruits, spices and tuber crops throughout Kerala (Rao *et al.* 2019, Alex and Menon 2022). Management of invasive weeds is a major concern all over the world. Vermicomposting is regarded as one of the effective methods in utilizing the weed biomass.

Banana (*Musa* sp.) is a major fruit crop in India, and it produces large quantities of plant residue after harvest, that contain remarkably higher amount of cellulose acting as carbon source for the microbes involved in composting, and potassium which can contribute significantly to the total potassium content of the vermicompost (Khalil *et al.* 2006, Saibaba *et al.* 2013). Therefore, vermicomposting of *A. bettzickiana* and banana pseudostem in various proportions was attempted to assess the suitability of the weed in mixed combinationas bio-organic manure, and to develop an effective strategy for the appropriate utilization of the weed.

The study was conducted during the period from September to December in 2021 at the Kerala Agricultural University (KAU), Thrissur Campus, Kerala. Fresh biomass of *A. bettzickiana* (root, stem and leaves) and banana pseudostem was collected from the farms and premises of the KAU, Thrissur Campus. Hatchlings of earthworm (*Eisenia fetida*) with an average weight of about 170-200 mg were obtained from the vermicompost unit situated in the campus. Weeds and banana pseudostem were chopped into small pieces of 4-5 cm to ease the action of earthworms. Mixed combinations of *A. bettzickiana* and banana pseudostem in different proportions (8:1, 4:1, 2:1, and 1:1) were compared along with sole use of *A. bettzickiana* in a completely randomized design (CRD) with four replications. Composting was carried out in cement rings of 1 m diameter and 0.5 m height and with concrete base. A layer of coconut husk was spread at the base of the ring, with the concave side upward, for easy drainage of excess water. Above the moistened husk, weed

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material, banana pseudostem, and cow dung were spread in alternate layers. The rings were filled up to the brim and sprinkled with cow dung slurry. The materials were left for partial decomposition, and earthworms were introduced on the 25th day at 500 numbers/ring. Water was sprinkled whenever necessary, and the materials were turned once in a week to ensure adequate aeration. After 70-80 days, compost was collected, heaped under shade for two days, and sieved to remove undecomposed materials.

Samples were collected initially on the day of earthworm release and at the end of experimentation for analysing various physico-chemical parameters like pH, electrical conductivity (EC), organic carbon, total nitrogen, phosphorus and potassium, and micronutrients (Fe, Zn, Cu). C/N ratio of the initial and final materials was also calculated. Initial weight (average weight before inoculation) and final weight of the worms collected from the rings after composting were recorded. Based on these observations, net biomass gains and growth rate/ worm/day were worked out. Significant differences between the treatments for various parameters were analysed using one-way ANOVA, and Tukey's test was performed at a significance level of a= 0.05 to distinguish homogenous groups among the treatments using WASP 2.0 statistical package.

Effect on physico-chemical properties of feed mixture and vermicompost

There was a decrease in pH in all the treatments relative to the initial values in the feed mixture due to the production of organic acids and carbon dioxide during the decomposition process (**Table 1**). Level of EC increased during vermicomposting, and a similar pattern was observed in the change of EC for all treatments, and the difference in EC among the treatments was found to be non-significant (**Table 1**). This rise in EC could be attributed to the release of mineral salts such as ammonium and phosphate ions during the decomposition of biomass.

Reduction in total organic carbon (TOC) was observed in all the treatments when compared to that of initial feed mixture. The highest reduction in TOC (52.5%) was observed in the treatment of only weed, and it was the lowest (40%) in weed + pseudostem (1:1). These results are in accordance with the findings of Yadav and Garg (2011) and Zhi-Wei *et al.* (2019) who reported 38-48 and 38.2-43.5% reduction in TOC with vermicomposting of *Parthenium hysterophorus* and rice straw + kitchen waste, respectively. About 20-43% of organic matter in the initial feed material was lost as CO_2 during vermicomposting,whereas digestion of polysaccharides and carbohydrates by the inoculated earthworms might also reduce the carbon content of the feed material (Elvira *et al.* 1998). Composting of weed material alone recorded the lowest TOC (22%). Treatments containing higher proportion of banana pseudostem recorded higher TOC (**Table 1**) which might be due to its higher lignin content, making the degradation difficult.

Enhancement in N, P and K content was observed in all the treatments. There was an increase in total N content to the extent of 29.5-50.0% during composting of *Alternanthera*. Similar results were reported by Sridevi *et al.* (2016) in vermicomposting of water hyacinth, which showed 51% increase in N content. Total N content was significantly higher in sole use of weed (1.67%) as well as mixed use of

Table 1. Physico-chemical properties of initial feed mixture and final vermicompost of different proportions of *A. bettzickiana* (weed) and banana pseudostem (pseudostem)

Treatment	pH	EC (dS/m)	TOC (%)	N total (%)	P total (%)	K total (%)	C:N ratio
Initial feed mixture							
Weed + pseudostem (8:1)	8.84^{a*}	1.51	49.1^{b}	1.12^{a}	0.66	0.79^{b}	43.8^{c}
Weed + pseudostem (4:1)	8.49^{ab}	1.23	53.2^{a}	1.03^{ab}	0.56	0.80^{b}	51.7^{c}
Weed + pseudostem (2:1)	8.29^{b}	1.26	54.9^{a}	0.93^{bc}	0.51	1.03^{a}	59.2^{b}
Weed + pseudostem (1:1)	8.30^{b}	1.21	56.1^{a}	0.85^{c}	0.48	1.08^{a}	66.3^{a}
Weed alone	8.81^{a}	1.48	46.3^{b}	1.11^{a}	0.64	0.71^{b}	41.7^{c}
LSD (p=0.05)	0.41	NS	3.11	0.11	NS	0.13	6.41
Final vermicompost							
Weed + pseudostem (8:1)	7.64	2.03	26.16^{b}	1.66^{a}	0.99^{a}	0.89^{b}	15.8^{c}
Weed + pseudostem (4:1)	7.60	1.80	30.29^{a}	1.33^{b}	0.78^{b}	0.97^{b}	22.7^{b}
Weed + pseudostem (2:1)	7.28	1.72	32.50^{a}	1.25^{bc}	0.75^{b}	1.31^{b}	25.9^{b}
Weed + pseudostem (1:1)	7.56	1.44	33.66^{a}	1.10^{c}	0.70^{b}	1.44^{a}	30.6^{a}
Weed alone	7.69	1.78	22.02^{c}	1.69^{a}	0.94^{a}	0.86^{b}	13.2^{c}
LSD (p=0.05)	NS	NS	3.91	0.17	0.16	0.11	3.22

*In a column, figures followed by the same letters do not differ significantly (Tukey, a=0.05) weed and pseudostem in 8:1 proportion (1.66%), where as it was the lowest (1.1%) in the mixture of1:1 proportion (**Table 1**). Plants belonging to Amaranthaceae family might be the efficient accumulators of nitrogen as evidenced from the present study. Nitrogen content in the leaves of *Alternanthera* was found to be 1.6-2.2% which might have caused higher total N content in the treatments with higher proportion of the weed biomass.

Increase in total P content during composting was in the range of 40.7-49.7%. Several P solubilizers inhabiting the earthworm gut produce phosphatase which is responsible for P mineralization during composting (Gopal *et al.* 2009). Significantly higher total P was recorded in weed + pseudostem mixture (8:1) and weed alone, which constituted higher proportion of *A. bettzickiana* biomass (**Table 1**). Easier degradability of weed biomass than that of pseudostem might enhance the earthworm and microbial activity, leading to higher rate of P mineralization.

An increase in total K content by 21-33% was observed during vermicomposting which might be ascribed to the release of certain acids by the microbes during the decomposition process that were responsible for the dissolution of organic potassium. Annathavalli *et al.* (2019) reported 58% increase in K content during vermicomposting of sea weed species (*Ulva reticulata*). Higher mineralization of K was reported in vermicomposting of water hyacinth than that in a system without earthworms (Sridevi *et al.* (2016)). Significantly higher total K content was recorded in weed + pseudostem in 1:1 proportion (1.44%) and 2: 1 proportion (1.31%) which constituted more amount of banana pseudostem (**Table 1**) due to remarkably greater concentration of K in banana waste as it luxuriantly consumes K from the soil.

C/N ratio, which is an indication of biomass stabilization and a criterion for accessing compost maturity, exhibited a sharp decline in all the treatments (**Table 1**). This might be due to loss of carbon as CO_2 during microbial respiration, enhanced mineralization of N in the organic matter and production of N containing compounds like mucus, hormones etc. by the earthworms. Among the treatments, weed + pseudostem (1:1) recorded significantly higher C/N ratio (30.6) while weed alone (13.2) and weed+ pseudostem in 8:1 proportion (15.8) recorded the lowest (**Table 1**). This might be attributed to lower organic C and higher total N content in compost obtained from these treatments.

Effect on micronutrient contents of feed mixture and vermicompost

Concentrations of micronutrients like zinc (Zn), iron (Fe) and copper (Cu) were observed to be slightly increasing during composting process (**Table 2**). Enhancement in the concentration of micronutrients through vermicomposting was also observed during composting of *Salvinia natans* (Singh and Kamaldhad 2016) and *Parthenium hysterophorus* (Yadav and Garg 2011). Modification of pH and microbial release of organic acids might cause the release of organically bound metals, leading to the increase in their concentration at the final stages of composting. Compost prepared from *Alternanthera* contained 123.5-146.7 ppm Zn, 3300.0- 3843.3 ppm Fe and 31.8-41.8 ppm Cu whilst the maximum limits of Zn and Cu in vermicompost were1000 and 300 ppm, respectively (GOI 1985).

Effect on earthworm growth and compost recovery

Growth rate of earthworms is an important factor determining the suitability of the raw material for the earthworms to work upon. The average weight of the worms during inoculation was 177.6 mg which increased to a range of 831.3-979 mg during harvest of the compost (**Table 3**). Significantly higher final biomass, net biomass gain and growth rate per worm was recorded in 8 weed: 1 pseudostem, 4 weed: 1 pseudostem and weed alone treatment. Growth rate of the worms depends upon the quality of the feed, feeding rate, constitution of easily digestible polysaccharides and growth promoting nutrients (Edwards *et al.* 1998). High

Table 2. Micronutrient contents in initial feed mixture and final vermicompost of different proportions of *A. bettzickiana* (weed) and banana pseudostem (pseudostem)

Treatment	Initial feed mixture			Final vermicompost		
	Zn (ppm)	Fe(ppm)	Cu (ppm)	Zn (ppm)	Fe (ppm)	Cu (ppm)
Weed + pseudostem (8:1)	114.1	3334.2	26.8	146.7	3488.3	37.3
Weed + pseudostem (4:1)	117.2	3610.8	31.7	137.7	3843.3	41.8
Weed + pseudostem (2:1)	110.3	3115.0	26.5	123.5	3300.0	33.7
Weed + pseudostem (1:1)	113.4	3386.7	24.9	128.7	3620.0	31.8
Weed alone	103.7	3430.8	26.2	127.9	3742.5	33.5
LSD (p=0.05)	NS	NS	NS	NS	NS	NS

Table 3. Earthworm growth during vermicomposting proportions of *A. bettzickiana* (weed) and banana pseudostem (pseudostem)

Treatment	Final biomass (mg)	Net biomass gain (mg)	Growth rate worm (mg/day)
Weed + pseudostem (8:1)	979.0[a*]	801.5[a]	11.4[a]
Weed + pseudostem (4:1)	964.0[a]	786.4[a]	11.2[a]
Weed + pseudostem (2:1)	831.3[b]	653.7[b]	11.2[b]
Weed + pseudostem (1:1)	842.6[b]	665.1[b]	9.34[b]
Weed alone	959.3[a]	781.7[a]	9.50[a]
LSD (p=0.05)	113.4	113.4	1.62

*In a column, figures followed by the same letters do not differ significantly (Tukey, *a*=0.05)

growth rate of earthworms in *A. bettzickiana* rich treatments can be attributed to the palatability, easy digestibility and nutrient availability of the weed biomass.

Based on the difference in initial weight of the feed mixture and final weight of the compost, compost recovery was found higher in the weed alone treatment (47%) and weed+ pseudostem at 8:1 (45.3%), followed by other proportions as 4:1 (36.1%), 2:1 (34.6%) and 1:1 (34%). Thus, higher proportion of *A. bettzickiana* proved to be more conducive for decomposition by earthworms with higher compost production.

It was concluded that *Alternanthera bettzickiana* biomass could be effectively utilized for the preparation of nutrient rich vermicompost. Enhancement of both macro and micronutrient contents in the vermicompost relative to the initial feed materials in all the treatments indicated the suitability of *A. bettzickiana* and banana pseudostem mixture for vermicomposting. Earthworm growth and biomass gain was within satisfactory range in all the treatments, indicating that the weed biomass could be successfully composted using *E. fetida*. Thus, the invasive weed, *A. bettzickiana* might be effectively utilized through its vermicomposting as a bio-organic manure.

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WORKSHOP REPORT

Stewardship guidelines for non-GM imazethapyr-tolerant rice in India

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ABSTRACT

Direct-seeded rice (DSR) is increasingly adopted due to its numerous advantages, including significant savings in water, labour, and time, reduced drudgery, lower production costs, improved soil health, and environmental benefits through reduced greenhouse gas emissions. However, high weed infestation and the emergence of weedy rice remain major challenges limiting its large-scale adoption. Selective herbicides are not available to control weedy rice. A promising solution lies in cultivating herbicide-tolerant (HT) rice varieties in combination with appropriate herbicide application. In India, non- transgenic imazethapyr-tolerant rice varieties such as Pusa Basmati 1979, Pusa Basmati 1985, and CR Dhan 807, along with hybrids SAVA 127 and SAVA 134, have been developed for commercial cultivation. To ensure the long-term sustainability of HT rice technology, strict stewardship guidelines are essential. This paper is an outcome of the deliberations of a workshop on "Stewardship Guidelines for non-GM imazethapyr-tolerant rice in India" organized at IRRI-SARC, Varanasi, on 4 October 2024.

Keywords: Direct-seeded rice, Imazethapyr-tolerant, Intgarted weed management, Non-GM rice, Weed

INTRODUCTION

Rice (*Oryza sativa* L.) plays a major role in sustaining global food and nutritional security, and meets 43% of the calorie requirement of nearly two-thirds of the Indian population (Shankari *et al.* 2023). India produces 137.83 million tonnes of rice from 47.82 million hectares of area with an average productivity of 2.88 t/ha (ASG 2023). By 2050, India needs to produce around 197.40 million tonnes of rice to meet the projected demand by a population of 1.65 billion. This represents an increase of more than 43% compared to current production. There is very limited scope for increasing the area under rice cultivation. With increasing temperature, water scarcity, changes in rainfall patterns, extreme climatic events such as floods and droughts due to global climate change, rice yields may decline significantly. In addition to negative impact on the soil health and water resource, rice cultivation contributes 7–17% to global methane (CH_4) emissions (Liu *et al.* 2022). Therefore, alternative crop establishment and management strategies which require less water, and emit less CH_4 from rice cultivation are urgently needed for sustainable rice production.

Direct-seeded rice (DSR), a resource conservation technology is gaining popularity as a potential alternative to the conventional puddled-transplanted rice (PTR) to reduce labour, water, energy and CH_4 emissions with increased economic returns. Compared to conventional PTR, the DSR has resulted in 76.2% less global warming potential (Tao *et al.* 2016), and 30-38% reductions in CH_4 emissions (Joshi *et al.* 2013). DSR can reduce greenhouse gas emissions by approximately 1.5 to 4.0 tons of CO_2 equivalent (CO_2e) per hectare per season. This translates to 1.5 to 4.0 carbon credits per hectare per season. In addition, DSR matures 7-10 days early and thus facilitates timely sowing of subsequent crops resulting in higher system productivity. Fast depleting water resources and rising labour scarcity have brought a paradigm shift in rice establishment from PTR to DSR in many countries including India. Despite potential benefits of DSR in terms of reducing water requirements and GHG emissions, improving soil health, and increasing resiliency to climate variability, severe weed infestation is a major concern in sustaining the productivity of DSR. If not managed promptly, weeds can reduce DSR yield

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ranging from 15-100%, posing a serious threat to farmers' productivity and food and nutritional security. Unlike traditional transplanting, DSR lacks the early head start advantage and natural weed suppression provided by field flooding.

Weed management by manual and cultural methods is restricted as they are labour-intensive and cumbersome in the context of increasing wages and labour scarcity. The development of new-generation, broad-spectrum pre- and post-emergence herbicides has opened new possibilities for DSR, addressing challenges of labour and water scarcity while providing crops with a critical early weed-free advantage, thus enhancing crop competitive-ness and weed control efficiency. Chemical weed management has largely replaced labour-intensive and physically demanding manual methods, making DSR more practical and economically viable. However, the success of herbicide use in DSR heavily depends on the precise timing of application tailored to specific crop and environmental conditions to ensure effective and lasting weed suppression. Repeated use of selective herbicides for weed management in DSR leads to the evolution of herbicide resistance in weeds. Crop sensitivity limits the application of broad-spectrum herbicides for effective weed management. In addition to complex weed flora in DSR, red rice/ weedy rice (*Oryza sativa* f. spontanea) has become a troublesome weed, causing a potential yield loss of 15 to 100% in DSR (Kumar and Ladha 2011). Weedy rice management in DSR is very difficult due to their morphological and genetic similarity with rice which hinders their targeted control using selective herbicides without injuring the rice crop.

Development of herbicide-tolerant (HT) rice varieties is one of the feasible and practical long-term solutions for sustainable weed management in DSR. With the advent of HT rice varieties, the spectrum of chemical weed control can be further exploited for flexibility in the timely application of herbicide and a wide-spectrum weed control including weedy rice without injuring the rice and the subsequent crops in rotation. Developing effective stewardship guidelines for HT rice utilization, creating awareness among farmers, crop rotation and integrating it with other weed management practices can help in realizing the fullest potential of HT rice varieties without any harmful effects on the environment and biodiversity.

Benefits of HT-rice technology

Herbicide-tolerant rice technology will facilitate the adoption of resource-efficient and cost-effective direct seeding of rice. Some of the key benefits of HT-rice include:

- Improved weed control with greater flexibility and reduced risk of crop phytotoxicity, especially for problematic weeds of DSR including weedy rice.
- Replacement of currently used herbicides with more efficient herbicides in controlling broad-spectrum weeds with better environmental profiles.
- New options to control weeds that have evolved resistance to currently used herbicides.
- Better crop establishment, more efficient use of nutrients and moisture, and higher crop yields.

Imazethapyr-tolerant HT rice techno-logy in India

India has introduced imazethapyr-tolerant HT rice varieties and hybrids, but their regulatory status remains contentious. Indian Council of Agricultural Research (ICAR)-Indian Agricultural Research Institute (IARI), New Delhi has developed and released two non-genetically modified (non-GM) HT Basmati rice varieties (Pusa Basmati 1979 and Pusa Basmati 1985). These varieties were developed through mutation breeding by altering the acetolactate synthase (ALS) gene, enabling tolerance to the herbicide imazethapyr. These varieties are particularly suited for DSR cultivation, offering benefits such as reduced water usage and labour requirements. Similarly, ICAR-CRRI Cuttack has also developed non-basmati rice variety '*CR Dhan 807*' tolerant to imazethapyr (Kar *et al.* 2024, ICAR-DWR 2025).

In addition, two HT rice hybrids (SAVA 127 FP and SAVA 134 FP) are being commercially cultivated by the rice growers. Some other companies are also working on development of non-GM HT rice varieties and hybrids (Dubey *et al.* 2022, Hubli 2022). This technology has been commercialized to address weed management challenges including management of weedy rice in DSR and to facilitate the transition from PTR to DSR.

STEWARDSHIP GUIDELINES

Stewardship guidelines for non-genetically modified (non-GM) imazethapyr-tolerant rice in India emphasize responsible use of herbicides to prevent the evolution of herbicide-resistant weeds and maintain crop productivity while minimizing environmental impact. Proper stewardship is crucial to ensure this technology's long-term viability and sustainability. Therefore, it is essential to develop and implement stewardship guidelines for imazethapyr-tolerant HT-rice technology that balances productivity gains with sustainability and risk mitigation.

A workshop was organized jointly by ICAR-DWR, Jabalpur, ICAR-IARI, New Delhi and IRRI, Philippines, on 1st December 2024 at ISARC, Varanasi, bringing together bureaucrats, researchers, industry representatives, and progressive farmers. During the workshop, all stakeholders shared their insights and experiences. Researchers and industry experts presented key findings, while farmers contributed practical perspectives from the field. From these discussions, several general and specific points emerged regarding the adoption and implementation of imazethapyr-tolerant HT rice technology.

For the longer-term use and sustainability of imazethapyr-tolerant HT rice technology it is important to implement the following stewardship guidelines.

Imperative requirement: Imazethapyr use should be limited to imazethapyr-tolerant rice varieties only.

1. **Integrated weed management program:** To achieve effective and sustainable weed management with imazethapyr-tolerant rice technology and to avoid/delay resistance evolution in weeds, the integrated weed management program given below is to be followed:

Herbicide program: Follow the label recommendation and integrate non-ALS herbicides in the herbicide program of imazethapyr-tolerant rice as given below:

Imazethapyr early post-emergence (12-14 days after sowing (DAS) or 2-4 leaf stage of weed) followed by imazethapyr as post-emergence at 25-30 DAS.

(or)

Recommended pre-emergence herbicides (pendimethalin, pyrazosulfuron, pretilachlor + pyrazosulfuron, pyrazosulfuron + pendimethalin, pendimethalin + penoxsulam, *etc*.) (apply within 3 days of sowing, if DSR is established in dry followed by irrigation, whereas under Tar-Watter DSR, apply immediately after sowing) followed by post-emergence application of imazethapyr at 18-20 DAS.

(or)

Imazethapyr early post (12-14 DAS or when weeds are 2-4 leaf stage) followed by post-emergence application of a non-ALS herbicide at 25-30 DAS or when weeds are 3-5 leaf stage if needed.

Note: In presence of diverse weed flora including some weeds which are not controlled by imazethapyr, either go with pre-emergence (pendimethalin, pyrazosulfuron, pretilachlor + pyrazosulfuron, pyrazosulfuron + pendimethalin, pendimethalin + penoxsulam, *etc.*) followed by imazethapyr or tank mix application of imazethapyr with a non-ALS herbicide as post-emergence. Always use the herbicides as recommended dose, time, and method of application as per the label claim. Use flat-fan nozzle for herbicide application.

- Avoid spray drift reaching the neighbouring non-HT rice and other crops susceptible to imazethapyr.
- Maintain good soil moisture during and following imazethapyr applications to get full efficacy.
- Use recommended pre-emergence/post-emergence herbicide(s) with alternate mode of action (non-ALS herbicides), as appropriate for comprehensive weed management.
- Scout for any leftover weeds and remove them manually before they set seeds.
- Follow stale seedbed technique to reduce the potential population density of weeds including weedy rice and volunteer rice from the previous season.
- Maintain irrigation channels and bunds free of weedy rice.
- Do not apply imazethapyr on non-HT/ conventional varieties in neighbouring field.
- Do not flood the field at the time of imazethapyr application.
- Apply uniformly all across field without escapes.

2. **Use quality seeds (certified/ truthfully labelled) as per the seed standards:** Farmers should use quality seeds of imazethapyr-tolerant varieties/ hybrids from authentic sources. In case of imazethapyr-tolerant hybrids, fresh seeds must be purchased from authorized sources every season.

3. **Gene flow risk management:** Following guidelines need to be adhered to minimize inadvertent gene flow into wild/ weedy rice.

I. In weedy/wild rice affected areas, make two applications of imazethapyr, one as early post-emergence at 12-14 DAS or at 2-3 leaf stage of weeds followed by second application at 25-30 DAS or when weeds are at 3-5 leaf stage to avoid any escape of weedy/wild rice plants.

II. Ensure rouging out escaped weedy/wild rice plants if any, by hand weeding before seed setting.

III. Weed stage should not cross 2-3 leaf stage at the time of application.

4. **Avoid continuous use of imazethapyr tolerant-rice varieties in the same field:** The sustainability of the technology depends on limiting the over-exposure of weeds to the herbicide. Therefore, it is recommended not to cultivate imazethapyr-tolerant rice for more than two consecutive growing seasons in the same field. Rotate imazethapyr-tolerant rice with conventional rice. Continuous use of imazethapyr-tolerant rice enhances the risk of faster resistance development in weeds and gene flow to weedy rice in weedy rice affected areas.

5. **Minimize carryover effects on succeeding crops:** Succeeding crops such as wheat and field peas could be taken up after imazethapyr-tolerant rice. However, for other succeeding crops that can be grown after the harvest of imazethapyr-tolerant rice, consult nearby SAUs/ ICAR institutions.

6. **Recommended management of volunteer rice plants:** Any of the following alone or in combination can minimize the problem of volunteer rice. These practices minimize other weed problems also.
   - Stale seedbed approach may be adopted to reduce the potential population density of volunteer rice from the previous season. This practice also reduces the density of other weeds including weedy rice.
   - Wherever feasible it is recommended to grow greengram/ blackgram as a catch crop or green manure crop during summer before seeding rice. By doing so, most of the volunteer rice get killed during land preparation for rice.
   - Wherever feasible, it is recommended to grow a crop other than rice after two years of imazethapyr-tolerant rice and ensure use of non-ALS herbicides.

7. **Capacity building of stakeholders:** Technology providers and public institutes should organize following capacity building activities:
   - Organize regular comprehensive training/ capacity building programs and awareness raising activities on Stewardship involving all stakeholders (researchers, farmers, input dealers, extension officers of KVK/FPOs/SHGs, industry personnel, *etc*.).
   - Technology providers to develop resource/ training materials and knowledge products as per the target groups.

8. Herbicide resistance monitoring committee

A committee for Herbicide Resistance Monitoring (HRMC) under the leadership of ICAR-Directorate of Weed Research with participation from public institutions such as ICAR institutions, SAUs, CGIAR institutions, and private organizations may be formulated to monitor the adherence of stewardship guidelines and the development of herbicide resistance, if any in areas where herbicide-tolerant rice cultivars are grown.

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