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OPINION ARTICLE

Revisiting weed research: Aspiring for more scientific methods, quality observations, and data analysis

T.K. Das¹, Tarun Sharma¹, Rishi Raj¹, Prabhu Govindasamy² and C.P. Nath³

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ABSTRACT

Crops and weeds may have differential response to resources/growth factors and environment under climate change, but little has been explored/investigated. The quantification of these effects/ responses needs rigorous basic and applied research. Necessarily, the weed research experiments should be pro-climate and tuned up to those directions, scales, and magnitudes, which could provide an edge to adapt to the changing climate and harness benefits more in favour of crops than weeds. Accordingly, the experiments and research methodologies/ observations need to be revisited/ reframed, having sound knowledge and science bases to make more authentic and climate-supportive recommendations. The pre-requisites are choosing pro-climate experiments and treatments, appropriate statistical design, relevant control/ check treatments for main and sub-plots, and precise sampling procedures, data tabulation and analysis, particularly for certain parameters like weed control efficiency, weed control index, weed index etc. The phytosociology study of weeds in crops across locations depict/ reveal community structure, diversity and similarity of weeds under changing climate and cropping practices and assumes huge significance. There is an utmost need to study the bio-efficacy of herbicides at weed species-level along with their effect on the categories of weeds and composite weeds to arrest species shift and dynamics. Studying the effect of herbicide/ weed control treatment on soil health (~carbon sequestration, physical, chemical and biological properties) and environmental health (herbicide residue in soil, water and crop produces, greenhouse gases emission, carbon footprints) has become highly pertinent and relevant now-a-days for climate resilient recommendation and sustainable crop production. Therefore, there is a need to pursue and expedite such research in collaboration with interdisciplinary sciences, which may be a comprehensive weed research model for future.

Keywords: Bio-efficacy, carbon footprint, data transformation, economic threshold, herbicide residue, weed interference indices

INTRODUCTION

Agriculture is a more subsidized artificial ecosystem (Odum 1975). Its energy flow (~40x10³ kcal/m²) has increased significantly compared to an unsubsidized natural ecosystem like grassland (~1x10³ kcal/m²). Crop production technologies have undergone a tremendous change over the years in pursuit of achieving higher crop yield through using high-yielding varieties, higher cropping intensity, newer crop sequence and increased level of inputs (fertilizer, irrigation, pesticides/herbicides). These have resulted in huge disturbances in natural vegetation and soil. Weeds are ubiquitous and eternal pest and have wider ecological amplitudes. Their species diversity and density/intensity are changing

continuously due to birth, death, immigration and emigration of weeds (Das 2008). This causes weed dynamics through sudden appearance or predominance of certain weed or a class of weeds, or sudden disappearance of certain weed from a crop/ cropping system; appearance of more vigorous forms of weeds like perennial weeds, resistant weeds, invasive weeds with time and space (Das 2001a). Climate, soil, physiography, and agro-practices like tillage, irrigation, fertilization, herbicides, and cropping systems highly influence weed dynamics. Therefore, a precise estimation of weed interference in a crop/cropping system and the impact of weed management options exercised is of paramount importance, which needs a sound methodology for appraisal. To develop weed science more as science, certain firm/ unalterable principles, basic theories/concepts/hypotheses, and certain standard, workable, and proven methodologies need to be framed up additionally and enshrined in weed science. These may be followed in weed research as applicable to the nature of an experiment and duly analyzed by using sound statistical tools.

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CROP-WEED INTERFERENCE APPRAISAL

Sampling procedures

Sampling under row-sown crops

Standard procedures must be followed for sampling weeds/ crop plants from the row-sown/ row-planted crops for precisely estimating the crop-weed interference, weed control treatments effects, and herbicide bio-efficacy. The throwing/use of quadrat arbitrarily/randomly in a plot/treatment is of no meaning since the quadrat size may not match the crop sowing geometry (row-row, plant to plant spacing) and arbitrarily chosen area may not be representative for crop-weed interference on the ground of unequal distribution of crop plants and weeds. Therefore, for sampling weeds and crop from a treatment plot, at first, one, two, or three rows of the crop (as available/allowable) up to certain lengths, or as such the length of quadrat should be selected as length of the sample area, and the row-spacing of one, two, or three rows of that crop as the width of the sampling area in the central location or across locations from which weeds and crop plants may be sampled for observations and recording of data (Figure 1). For this kind of sampling, a quadrat may or may not be used/required and the area of sampling may or may not be equal to the area of quadrat as well. For example, in a maize crop having 60 cm (row-row) x 30 cm (plant-plant) spacing, a 90 cm or so (along the rows; ~3 plants or so) x 60 cm or so (across the rows; ~1 row or so) may be randomly selected from the central rows in each plot. Weed species and maize plants may be collected from that area. Individual weed species may be counted, categorized into grassy, broad-leaved, sedges or

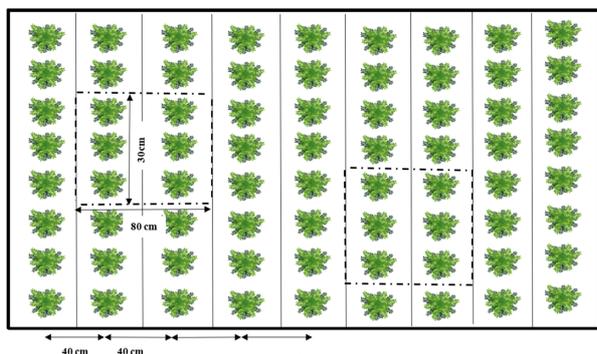


Figure 1. Weed sampling technique for row-sown crops having distinct plant to plant spacing (40 cm row-row x 10 cm plant-plant; sampling area is 0.24 m²). In case of continuously-sown tillering crops like rice, wheat, row to row distance may be like this, but along the rows, length may be arbitrarily taken or taken as the length of the quadrat (if used)

perennial weeds and summed up to total weed density across the treatments. Later the dry weight may be determined, following usual oven-drying procedure. Similarly, crop sample may be taken from that area for precisely estimating crop-weed interference (Figure 1). Multiple samples may be collected using quadrat from a plot bigger than 30 m².

Sampling under broad-cast/mixed-sown crops

In broadcast/mixed-sown crops, a sampling area (without quadrat) having uniform crop stand and weeds may be randomly chosen or a quadrat of suitable size may be thrown randomly at the central locations of the plot avoiding borders rows and weeds may be collected from that area (Figure 2). For a bigger plot greater than 30 m², multiple samples using quadrats from 3-4 locations of a plot/treatment may be collected. However, under the both row-sown and mixed-sown crops, the sampling area should be selected in such a way that it should have weed distribution representative to the whole plot/treatment. Similarly, crop samples may be taken from this area for appraising crop-weed interference.

Fixed/tagged /undisturbed plot study

The tagged fixed/undisturbed plots constitute a kind of component study. This is usually done within an experiment having larger plot area, executed for a longer period and data need to be generated out of this experiment on treatments' effects, weed distribution and flora shift, weed seed bank, *etc.* (Figure 3). For this kind of experiment, a few small fixed/tagged plots (usually 2 m x 2 m or bigger) are randomly selected/ earmarked/ delineated in each treatment/ plot of larger dimension replication-wise, mainly, for non-destructive observations (*e.g.*, periodical weed and crop plants density, plants height, *etc.*). These plots may also be used for destructive sampling of weed dry weight, weed seed bank, crop plants tillering, branching, leaf area, yield attributes *etc.* For

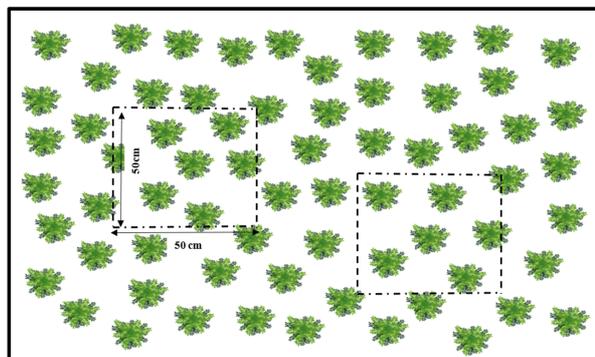


Figure 2. Weed sampling technique for broadcasted single crop or mixed cropping plots using a quadrat of 50 cm x 50 cm

destructive sampling, the number of fixed plots per plot should be kept in large number or otherwise the fixed plot size may be kept larger. Interventions like inter-culture, herbicide application, hand weeding etc should not be done in these fixed plots except the treatments/ agro-practices being adopted since long time.

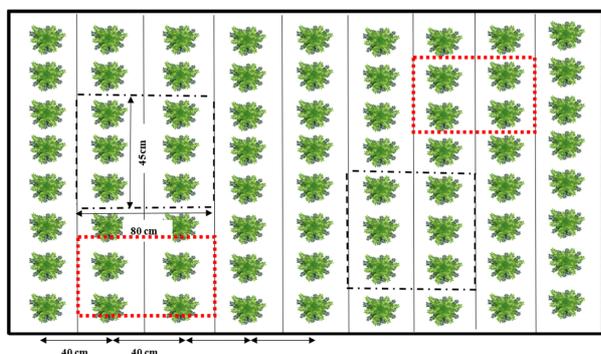


Figure 3. Weed sampling technique from a fixed/undisturbed plot in long-term studies for generating data on weed diversity, succession/flora shift, weed seed bank, etc. Main plot treatments like cropping practices, nutrients management etc may be applied to whole plot including the Red-bordered area, which will be kept fixed/undisturbed over the years and blanket weed management practice may be adopted to keep the plot free from weeds or a few other weed control treatments superimposed in this plot.

CROP-WEED INTERFERENCE INDICES

Weed control efficiency (WCE) and per cent reduction in weed density

Weed control efficiency (WCE) is derived from weed density for studying the performance of a treatment in terms of reduction in weed density compared to weedy check/ unweeded control (Mani *et al.* 1973). Weed density although may not be an accurate and reliable estimate for studying weed interference/control in a crop, the trend in the efficiency of the methods/treatments adopted may be appraised in terms of their superiority/inferiority. The WCE may be calculated using the following formula (Eq.1):

$$WCE = \left[\frac{WD_c - WD_T}{WD_c} \right] \times 100 \quad (1)$$

Where, WD_c and WD_T are weed density (number/m²) in control and treated plots, respectively; The unit in both WD_c and WD_T should be same.

This derived parameter may strictly be pronounced as WCE, when the per cent reduction in weed density of the treated plots/ treatments is

compared based on a weedy check/unweeded control treatment adopted in the experiment. Otherwise, it may be pronounced as the per cent reduction in weed density of a treatment compared with another treatment adopted in the experiment, having no absolute weedy check/unweeded control treatment. The similar formula (Eq.1) may be used with no mention of weedy check /unweeded control treatment (Eq.2).

Per cent reduction
in weed density = $\left[\frac{(WD_{Tc} - WD_{Tn})}{WD_{Tc}} \right] \times 100 \quad (2)$

Where, WD_{Tc} is weed density in T_c treatment based on which the per cent reduction is being calculated in another treatment T_n having weed density WD_{Tn} ; The unit in both WD_{Tc} and WD_{Tn} should be same. T_c is the control/check treatment whose density is taken as base value for calculating the per cent reduction in the “nth” number of treatment (where $n = 1 \dots n$). T_n is the nth treatment for which the per cent reduction is being calculated over the T_c .

Weed control index (WCI) and per cent reduction in weed dry weight

Weed control index is calculated based on reduction in weed dry weight compared to weedy check/ unweeded control (Misra and Tosh 1979). In the formula of WCE of Mani *et al.* (1973), weed density has been replaced with dry weight to calculate WCI. It is a more reliable estimate for studying weed interference /control in crops across the treatments than WCE. The WCI may be calculated using the following formula (Eq.3):

$$WCI = \left[\frac{(WDW_c - WDW_T)}{WDW_c} \right] \times 100 \quad (3)$$

Where, WDW_c and WDW_T are weed dry weight (unit/m²) in control and treated plots, respectively; The unit in both WDW_c and WDW_T should be same. The similar formula (Eq.3) may be used where weedy check /unweeded control treatment has not been considered (Eq.3).

Per cent reduction
in weed dry weight = $\left[\frac{(WDW_{Tc} - WDW_{Tn})}{WDW_{Tc}} \right] \times 100 \quad (4)$

Where, WDW_{Tc} is weed dry weight in T_c treatment based on which the per cent reduction is being calculated in another treatment T_n having weed dry weight WDW_{Tn} ; The unit in both WDW_{Tc} and WDW_{Tn} should be same.

The values of WCE and WCI usually vary from 0 (zero) to 100. On principle, the WCE and WCI of

the weedy check should be always zero (0) and that of the weed-free check treatment always 100. Thus, higher the WCE or WCI of a treatment, greater is its weed control potential. However, there are instances in which the WCE and WCI have been found to be negative (-ve) for a treatment, which was worse than weedy check. It may happen in field experiments. They can be worked out for both sole and intercropping situations. In a crop/season, the WCE/WCI of a treatment, particularly, herbicide may increase/ decrease over time depending on the growth/vigour of a crop, nature and spectrum of weeds, herbicides, growing season/environment, *etc.*

It would be always better/wiser to use the original non-transformed data for calculating the WCE and WCI, although a researcher can use both transformed and non-transformed original data. This would reflect the actual WCE/WCI of a particular treatment. This would hardly be reflected by using the square-root or logarithmically transformed weed data. Using the transformed weed data, the WCE/WCI of a treatment would never become 100% as usually obtained for the weed-free check treatment. However, the non-transformed original data would always lead to 100% WCE/WCI for the weed-free check treatment.

Weed index (WI) and per cent reduction in yield

Weed index (WI) is crop yield reduction across the treatments compared to weed-free check treatment in weed control experiments (Gill and Vijayakumar 1969). It is also called as weed competition index (WCI). Here the control treatment is always weed-free check. The WI appraises the superiority/ inferiority of a treatment in terms of crop yield and is worked out in almost all weed control studies. The WI may be calculated based on the following formula (Eq.5):

$$WI = \left[\frac{Y_{WF} - Y_T}{Y_{WF}} \right] \times 100 \quad (5)$$

Where, Y_{WF} and Y_T are crop yield in weed-free plot and treatment plot, respectively; The unit should be same in both Y_{WF} and Y_T .

$$\text{Per cent reduction in crop yield} = \left[\frac{(Y_{Tc} - Y_{Tn})}{Y_{Tc}} \right] \times 100 \quad (6)$$

Where, Y_{Tc} is crop yield in treatment control based on which the per cent reduction is being calculated in another treatment T_n , whose yield is Y_{Tn} ; The unit should be same for both Y_{Tc} and Y_{Tn} .

Weed index (WI) is determined in several experiments, which do not have any weed-free treatment. In such cases, the best weed control treatment or the lowest weed-infested plot such as

two/three hand weeding or alike has been considered as weed-free control. Theoretically/on principle, weed-free check is completely free from weeds and can hardly be substituted/replaced with any weed control treatment even though it is assumed to be the best weed control treatment. In that case, it should be strictly pronounced as the per cent yield reduction rather than WI. In an extreme case of weedy check where no yield is obtained, WI becomes 100. The WI of weed-free check is always 0 (zero). However, certain treatments, particularly some efficient herbicides, in which higher yields obtained than in season-long weed-free control, may have WI values negative (-ve), which indicates superiority of that treatment than even weed-free check. WI could be worked out for both sole and intercropping situations.

Species- and category-wise weed appraisal

For determining WCE and WCI, respectively, the density and dry weight of composite culture of weeds across the treatments are taken into consideration. This ignores the importance/ effect of specific/single weed species. For this, the species-wise density and dry weight of weeds are considered and could be achieved through sampling of weed species individually from a certain area using quadrat. This, upon summing up of weeds of particular category, may further lead to category-wise density and dry weight of weeds. The relative density (Rdn) (Eq.7) and relative dry weight (Rdw) (Eq. 8) of a weed species can be studied to evaluate its effect to the overall total effect of composite weed community.

$$Rdn = \left(\frac{W_{dn}}{TW_{dn}} \right) \times 100 \quad (7)$$

$$Rdw = \left(\frac{W_{dw}}{TW_{dw}} \right) \times 100 \quad (8)$$

Where, W_{dn} and TW_{dn} are densities of a weed species and total composite weeds present in that area, respectively; W_{dw} and TW_{dw} are dry weight of a weed species and total composite weeds present in that area, respectively.

Several other indices related to weed interference, crop tolerance/ competitiveness (Mishra and Misra 1997) or weed control performance (Krishnamurthy *et al.* 1975) are weed smothering efficiency (WSE) in intercropping situations), weed persistence index (WPI), crop resistance index (CRI), pest/weed management index (PMI/WMI), agronomic management index (AMI), integrated pest/weed management index (IPMI/IWMI), and herbicide efficiency index (HEI) (Eq.9-Eq.15). All these have got enough relevance to study the aspects

of weed management on comparative basis/scale among treatments.

$$WSE = \left[\frac{(M_{dw} - I_{dw})}{M_{dw}} \right] \times 100 \quad (9)$$

$$WPI = \frac{\text{Weed density in control plot}}{\text{Weed density in treated plot}} \times \frac{\text{Weed dry weight in treated plot}}{\text{Weed dry weight in control plot}} \quad (10)$$

$$CRI = \frac{\text{Crop dry weight in treated plot}}{\text{Crop dry weight in control plot}} \times \frac{\text{Weed dry weight in control plot}}{\text{Weed dry weight in treated plot}} \quad (11)$$

$$PMI/WMI = \frac{\text{Per cent crop yield over control}}{\text{Per cent control of weeds/other pests}} \quad (12)$$

$$AMI = \frac{\text{Per cent crop yield over control} - \text{Per cent control of weeds/other pests}}{\text{Per cent control of weeds/other pests}} \quad (13)$$

$$IPMI/IWMI = \frac{(PMI+AMI)}{2} \quad (14)$$

$$HEI = \left[\frac{\left(\frac{Y_T - Y_C}{Y_T} \times 100 \right)}{\left(\frac{Wdw_T}{Wdw_C} \times 100 \right)} \right] \quad (15)$$

Where, Y_T is crop yield from the treated plot; Y_C is crop yield from the weedy check; Wdw_T is weed dry weight in the treated plot; and Wdw_C is weed dry weight in the weedy check plot.

WEED INTERFERENCE STUDY

Agronomic non-weed control experiments

In several agronomic experiments so-called not purely weed control experiments, researchers strive to study relative weed control effects of the treatments so-called non-weed control treatments without adopting any designated weed control check treatment like weedy check, weed-free check, standard herbicide check as applicable. Weed population and dry weight are studied as additional/extra data to highlight the effects of some non-weed control treatments like fertility levels, nutrients, cropping systems, or agro-practices on weed interference/ weed growth reduction. Also, weed control efficiency (WCE), weed control index (WCI), and weed index (WI) are calculated in these experiments. The WCE and WCI based on weed population and dry weight, respectively are calculated/reported across the treatments considering one traditional treatment (like no or full nutrients application against other set of nutrients, no or full water application against other water treatments, conventional till agriculture against no/minimum tillage practices etc.) as control out of a set of treatments adopted. However, this should not be so. Therefore, an attempt has been made here to highlight

the myth and reality of WCE versus per cent reduction in weed density, WCI versus per cent reduction in weed dry weight, and WI versus per cent reduction in crop yield. These experiments do not have the requisite control or check treatments like weedy check/ unweeded control for studying WCE/ WCI and weed-free check for studying WI. No disagreement/worry in that the basic/elementary data on weed population and dry weight are observed across the treatments in these experiments and the superiority or inferiority of a treatment is compared with other treatments based on the reduction in weed population and dry weight. But, giving term as WCE, WCI or WI, is not appropriate when these are calculated considering one treatment out of the whole set of treatments as control, which is not the absolute control. The WCE, WCI and WI are derived parameters using appropriate formulae and should not be same/similar with what has been calculated without having a designated control treatment. For these cases, the designated term should be the per cent reduction in weed population instead of WCE, per cent reduction in weed dry weight instead of WCI, and the per cent reduction in crop yield instead of WI considering that traditional control treatment. Otherwise, it has been seen that the results/ data calculated from these experiments may lead to some arbitrary, absurd, and illogical inferences. Therefore, the derivation of per cent reduction in weed density, per cent reduction in weed dry weight, and per cent reduction in crop yield uniformly apply to all experiments, irrespective of agronomic and weed control research with or without designated control treatments and sound more universal than WCE, WCI and WI, respectively.

Scenario 1: Experiment in randomized complete block design, considering one non-weed control treatment as control but not an absolute control

Recently, research is being carried out in several frontier areas such as conservation agriculture, organic farming, natural farming, precision farming on several aspects of agronomy, soil health, crop protection, environmental implications, etc. This large theme area usually entertains a number of objectives to be investigated on a time-scale. Therefore, under a long-term bigger experiment of this kind, several small component trials are undertaken to satisfy several objectives or sub-objectives. In several agronomic non-weed control experiments, researchers intend to study weed control efficiency/weed control index (WCE/WCI) without an absolute control treatment. Experiments are laid out in randomized complete block design and

considered a non-weed control treatment as control and analysed for WCE/WCI. An experiment of this kind is of Ghosh *et al.* (2022), involving several conservation agriculture practices (Table 1), and WCE/WCI was studied. Treatments were conventional tillage flatbed without residue (CT); ZT permanent narrow bed without residue (PNB) and with residue (PNB+R), ZT permanent broad bed without residue (PBB) and with residue (PBB+R); ZT flatbed without residue (PFB) and with residue (PFB+R). The 100%N (100N) and 75% (75N) of the recommended doses were applied to residue-retained conservation agriculture (CA) plots like PNB+R, PBB+R and FB+R treatments. To assess WCE/ WCI of this experiment, an area (~mini plot/ spot) of 2 m x 2 m was tagged/ earmarked in each treatment plot, which remained unsprayed/ unweeded throughout the crop cycle and weed data were collected from these spots to find out the effect of these non-weed control CA treatments. The CT had higher weed growth but the CA-based practices had lower weed growth and variable weed suppression ability. Therefore, CT was considered as the control, although it was not an absolute control like unweeded/weedy check control but a relative one for the purpose of studying WCE and WCI. In this kind of evaluation of relative weed suppression ability of the treatments, WCE and WCI may not sound appropriate as followed for the true weed control experiments. It would be better if per cent reduction in weed density instead of WCE, and per cent reduction in weed dry weight instead of WCI are mentioned/ used in this kind of studies. However, in this kind of experiment involving required absolute controls like weedy check (WC) or unweeded control (UWC), and weed-free check (WFC) along with these treatments (CT, PNB, PNB+R, PBB, PBB+R, FB, FB+R), the WCE, WCI, and weed index (WI) may be worked out.

Table 2. Total weed population and weed control efficiency (WCE) and index (WCI) at 40 DAS of maize (Part of the Table 1 of Susha *et al.* 2014)

Treatment	WCE (%)	WCI (%)
Weedy check	0	0
Atrazine 0.75 kg/ha + pendimethalin 0.75 kg/ha (tank-mix PE)	69.6	74.4
Atrazine 1.0 kg/ha + hand weeding at 30 DAS	78.4	87.0
Atrazine 1.0 kg/ha +mustard residue mulch 5 t/ha	66.4	74.8
Pendimethalin 0.75 kg/ha + imazethapyr 0.050 kg/ha (tank-mix PE)	90.6	90.9
*KNO ₃ (6%) + pendimethalin 0.75 kg/ha + imazethapyr 0.050 kg/ha (tank-mix PE)	89.2	87.3
Pendimethalin 0.75 kg/ha + chlorimuron 0.006 kg/ha (tank-mix PE)	85.6	85.3
Pendimethalin 0.75 kg/ha PE followed by imazethapyr 0.050 kg/ha PoE with sand	78.1	76.8
Pendimethalin 0.75 kg/ha PE <i>fb</i> chlorimuron 0.006 kg/ha POE with sand	75.5	74.0
Brown manuring (<i>Sesbania</i> 5 kg/ha+ 2,4-D 0.75 kg/ha at 25 DAS)	59.8	60.3
Brown manuring (<i>Sesbania</i> 10 kg/ha+ 2,4-D 0.75 kg/ha at 25 DAS)	64.6	67.7
Weed-free check	100.0	100.0

*KNO₃ was applied separately; PE - pre-emergence; PoE – post-emergence; **Data were subjected to square-root ($\sqrt{x+0.5}$) transformation; Figures in the parentheses are original values

Table 1. Conservation agriculture treatments effects on weed control efficiency (WCE)/per cent reduction in weed population, weed control index (WCI)/ per cent reduction in weed dry weight (WCE) in mungbean (Part of the Table 1 of Ghosh *et al.* 2022)

Treatment	WCE (%) in 2018-19	WCI (%) in 2018-19
CT	0	0
PNB	16.3	6.7
PNB+R+75N	38.0	42.2
PNB+R+100N	30.4	47.3
PBB	44.6	36.7
PBB+R+75N	51.1	50.2
PBB+R+100N	45.7	48.9
FB	31.5	35.1
FB+R+75N	37.0	39.3
FB+R+100N	34.8	38.3

Scenario 2: Experiment in randomized complete block design having absolute controls (WC/ UWC, WFC)

A case in point is the experiment of Susha *et al.* (2014), which is a pure/true weed control trial (Table 2), involving 11 weed control treatments including two controls such as WC and WFC. Here studying WCE and WCI is very appropriate, which really gives a measure of relative weed control ability of these treatments. For example, highest WCE and WCI were obtained from the tank-mix pre-emergence application of pendimethalin 0.75 kg/ha + imazethapyr 0.050 g/ha. With respect to WCE and WCI, all the weed control treatments including brown manuring showed superiority over weedy check (WC).

Scenario 3: Experiment in split plot design considering only one control for both main plot and sub-plot treatments (may/may not be absolute control)

In some experiments in split plot design, one set of weed control treatments are adopted out of two

sets of treatments and analyzed, taking only one control for both main plot and sub-plots treatments (Table 3). Fazil *et al.* (2022) conducted an experiment involving three weed management options in main plots, and four N levels in sub-plots in barley. For both main plot and sub-plot treatments, weedy check was taken as control for determining WCE and WCI, whereas WFC was the control for determining WI. It showed that the IWM significantly increased WCE and WCI. On the contrary, the effect of nitrogen levels was not significant although the N-treatments gave considerably higher WCE/WCI values ranging from 34-52%. In this case, the effect of each main plot weed control treatment averaged over four sub-plot N treatments and compared with WC is alright and acceptable as the efficacy/effect of the weed control treatments got tested/ evaluated over a range of N doses. But, the effect of each sub-plot N treatment averaged over three main plot treatments and compared with WC gave values hardly acceptable as their individual effect since the values are quite higher and could hardly be achieved under field conditions.

For example, it shows that N₁₂₀ can lead to 51.6% WCE and 44.3% WCI, which hardly can happen in reality. This could happen due to the statistical analysis. The effects of all weed control treatments have been averaged and reflected in the N doses. In this sort of experiment, the WCE/WCI should be worked out only for the factor, main plot or sub-plot that involves the weed control treatments with WC (~W₁) as the control, which will be quite realistic and reasonable. The WCE/WCI of the other

Table 3. Weed control efficiency (WCE), weed control index (WCI) at 40 DAS and weed index/WI in barley (Part of the Table 1 of Fazil *et al.* 2022) (considering one absolute control for both main plot and sub-plot treatments)

Treatment	WCE (%)	WCI (%)	Weed index (%)
<i>Weed management (W)</i>			
Weedy check (W ₁)	0	0	24.1
Chemical weed management (W ₂)	60.7	58.6	6.6
Integrated weed management (W ₃)	81.9	72.6	0.0
LSD (p=0.05)	7.96	14.8	10.4
<i>Nitrogen doses (N)</i>			
N ₀	40.0	44.3	41.1
N ₄₀	43.9	34.2	18.5
N ₈₀	54.8	52.2	-6.7
N ₁₂₀	51.6	44.3	-11.9
LSD (p=0.05)	NS*	NS*	19.8
<i>Interaction (WxN)</i>			
LSD (p=0.05)	NS*	NS*	NS*

* Non-significant

factors should not be studied/reported. To establish their actual WCE/WCI, they should be studied as an individual treatment solely in a randomized complete block design and compared with WC. However, their combined interaction effect if at all exists on WCE/WCI may be studied and reported. Furthermore, in this case, the calculation is more complex and each pair of W₁N₀, W₁N₄₀, W₁N₈₀, and W₁N₁₂₀ have to be taken as control for determining the WCE/WCI of respective pairs of W₂ with N₄₀, N₈₀&N₁₂₀, and W₃ with N₄₀, N₈₀ & N₁₂₀ treatments (Table 3a). For easy and quick analysis, sometimes only one combination of main plot control and sub-plot control such W₁N₀ is taken as single control, and the WCE/WCI of rest of the combinations are worked out. This may lead to erroneous analysis and inference (Table 3b) and should not be adopted in any case/ experiment. Doing this, the mean value of WCE/WCI even for the weedy check control (W₁) treatment does not become zero. Another analysis could be that two controls are chosen separately, such as W₁ for main plot (weed control treatments) and N₀ for the sub-plot (N doses) treatments and both factors' effects are analyzed separately (Table 3c). This has been presented in Table 4.

Table 3a. WCE or WCI calculated considering only one main plot treatment as control for combination with each of the sub-plot treatments

Treatment	WCE or WCI across the combinations of treatments				Mean
	N ₀	N ₄₀	N ₈₀	N ₁₂₀	
W ₁	0	0	0	0	0
W ₂	a ₁	a ₂	a ₃	a ₄	A
W ₃	b ₁	b ₂	b ₃	b ₄	B
Mean	C	D	E	F	

Here W₁ to W₃; N₀ to N₁₂₀ are taken from Table 3; Each pair of W₁N₀, W₁N₄₀, W₁N₈₀, and W₁N₁₂₀ are taken as control; a₁- a₄ & b₁- b₄ are replication-wise values of WCE/WCI calculated based on weed density or dry weight; and A-F are respective mean values of WCE/WCI of the main plot and sub-plot treatments.

Table 3b. WCE or WCI calculated considering only one combination of treatments (W₁N₀) as control

Treatment	WCE or WCI across the combinations of treatments				Mean
	N ₀	N ₄₀	N ₈₀	N ₁₂₀	
W ₁	0	a ₁	a ₂	a ₃	A
W ₂	b ₁	b ₂	b ₃	b ₄	B
W ₃	c ₁	c ₂	c ₃	c ₄	C
Mean	D	E	F	G	

Here W₁ to W₃; N₀ to N₁₂₀ are taken from Table 3; Only W₁N₀ is taken as control; a₁- a₃; b₁-b₄&c₁-c₄ are replication-wise values of WCE/WCI calculated based on weed density or dry weight; and A-G are respective mean values of WCE/WCI of the main plot and sub-plot treatments.

Table 3c. WCE or WCI calculated considering two controls one each for main plot and sub-plot treatments

Treatment	WCE or WCI across the combinations of treatments				Mean
	N ₀	N ₄₀	N ₈₀	N ₁₂₀	
W ₁	0	0	0	0	0
W ₂	0	a ₁	a ₂	a ₃	A
W ₃	0	b ₁	b ₂	b ₃	B
Mean	0	C	D	E	

Here W₁ to W₃; N₀ to N₁₂₀ are taken from Table 3; Each pair of W₁N₀, W₁N₄₀, W₁N₈₀, and W₁N₁₂₀, and N₁W₁, N₁W₂, and N₁W₃ are taken as control; a₁- a₃& b₁- b₃ are replication-wise values of WCE/WCI calculated based on weed density or dry weight; and A-E are respective mean values of WCE/WCI of the main plot and sub-plot treatments.

There is no WFC treatment in this experiment (Table 3), but WI has been calculated. The IWM treatment being most superior in terms of higher WCE/WCI and crop yield, was considered as the control, i.e. WFC. This, however, should not be followed. In reality, an IWM treatment can never substitute WFC theoretically. This has been found in many weed experiments and two hand weeding, three hand weeding, or the best weed control treatment have been considered as control/WFC treatment and WI calculated. There is nothing wrong in determining this parameter. But, in this case as there was no WFC treatment, it would be more appropriate to mention it as the per cent reduction in crop yield based on the so-called control. This can be compared with all other treatments in randomized complete block design, and across the main plot treatments or across the sub-plot treatments as applicable in split plot design. The per cent reduction in crop yield is more universal than WI and can be applicable/determined uniformly in all weed/non-weed agronomic experiments.

Scenario 4: Experiment in split plot design taking two controls one each for main plot and sub-plot treatments (may or may not be absolute control)

In some experiments in split plot design, involving two sets of treatments as main plot and sub-plot, WCE/WCI or WI are worked out considering two controls, one main plot treatment as control for the main plots and one sub-plot treatment as control for the sub-plots and statistical analysis is done. Kumar *et al.* (2012) had undergone similar analysis in an experiment involving five main plot and four sub-plot treatments (Table 4). By doing this, the main plot treatments averaged over sub-plots treatments are compared among themselves, while sub-plot treatments averaged over main plot treatments are compared among themselves.

Table 4. *Cyperus rotundus* control efficiency (CCE) and *C. rotundus* control index (CCI) of different treatments in soybean (Part of the Table 6 of Kumar *et al.* 2012) considering one control each for main plot and sub-plot treatments)

Treatment	CCE (%)	CCI (%)
<i>Summer season</i>		
Cowpea cropping	13.9	12.3
Deep disking <i>fb</i> glyphosate at 1.0 kg/ha once	25.5	19.2
Deep disking <i>fb</i> glyphosate at 1.0 kg/ha twice	55.0	48.5
Soil solarization for one month <i>fb</i> glyphosate at 1.0 kg/ha	83.5	83.1
Farmers' practice	-	-
<i>Rainy season</i>		
Unweeded control	-	-
Imazethapyr at 0.075 kg/ha at 20 DAS	51.5	77.9
<i>In situ Sesbania</i> grown and mulched	55.5	72.1
Two hand-weeding at 25 and 35 DAS	83.8	91.4

WEED DATA TRANSFORMATION: MYTHS AND REALITY

The non-uniform scattered distribution and periodicity of germination of weeds coupled with the effect of treatments like weed-free check, weedy check, adopted in most experiments often results in large variation. Transformation helps to normalize these data. Several transformations, *viz.*, square-root, logarithmic, angular or reciprocal are advocated for different purposes (Table 5). Therefore, an analytical exercise (Das 1999) had been undertaken to find out whether transformation could change the significance of weed data across treatments; whether the square-root transformations varied among themselves; whether a wider variation in significance of data existed between the square-root and logarithmic methods *vis-à-vis* between the split plot and randomized complete block design. Original and transformed data through $(X+1.0)^{1/2}$, $(X+0.5)^{1/2}$, $(X+0.05)^{1/2}$ and $\log(X+1)$ were subjected to analysis of variance (ANOVA) and the significance was tested by variance ratio/ F value. The summum bonum of the ANOVA revealed that (i) the significance for treatment variation of the main plots, sub-plots and their interaction did not differ between original and transformed data, irrespective of square-root and logarithmic methods up to a coefficient of variation (CV) nearly 70%; (ii) at the CV higher than 100%, the square-root transformed data behaved similarly with original data, but the logarithmic transformation differed with original data (Das 1999); (iii) different square-root methods tried did not differ among themselves; and (iv) transformation could reduce CV by 50% in square-root methods and by 75% in logarithmic method and standard error drastically.

Table 5. Different methods of data transformation (Das 2008)

Transformation method	Formula	Data to be transformed
Square-root methods	$(X+1.0)^{1/2}$; $(X+0.5)^{1/2}$; $(X+0.05)^{1/2}$ (where X is value of an observation)	Weed data (population, dry weight, <i>etc.</i>)
Logarithmic methods	Log (X+1) (where X is value of an observation); Log X should not be adopted as Log 0 becomes infinitive	Weed data (population, dry weight <i>etc.</i>)
Angular/arcs in method	$\text{Sin}^{-1}X$ (where X is per cent value of an observation)	Insect population, fecundity, or any per cent data
Reciprocal method	1/X (where X is value of an observation)	Hardly used in weed research

Therefore, a hypothesis is made that the transformation of weed data through square-root or logarithmic methods is not an unavoidable one. It should not be followed indiscriminately except where the data required it. It is generally-held that the desired level of CV for field research data should not exceed 20%. But, most weed data, usually possess a larger variation than this, and at this level of variation, transformation found useless. Therefore, Finney (1989) viewed that the assumptions/pre-requisites for ANOVA of data are never certain and not so important to the general informativeness of the analysis. In those situations, where original and transformed data show similar test of significance, it would be better for several reasons that the original data analysis is highlighted (Das 1999).

WEED SURVEY AND PHYTOSOCIOLOGY STUDIES

Sampling of weeds in surveys

Generally, in a weed survey, the sampling area is 5-10% of the total surveyed area. Surveys identify and analyze weeds in order to formulate effective management approaches. Weed phytosociology (frequency, density, abundance, dominance, importance value index/IVI), similarity/ dissimilarity/ shift, mapping, management effectiveness, and insurgence of resistant weeds may be evaluated. Surveys encompass crops, orchards, agro-forestry systems, irrigated/ rainfed crops across villages, blocks, districts, agro-climatic regions based on the magnitude of problem of weed/ invasive weed and objective of survey. Sometimes, herbicide application in crop fields influences time of sampling. It should be decided whether to sample with or without herbicide treatment well before sampling. Sampling from no herbicide treated plots reflects the potential weed distribution and is useful to analyse site and management effects other than herbicides. Herbicide effects can superimpose all other influences in the current crop (Andreasen *et al.* 1991; Mehrtens *et al.* 2005).

Phyto-sociological studies may adopt destructive or non-destructive method, which has inherent advantages and disadvantages. In destructive

sampling, plants are pulled out/ cut at the base and their population count, fresh and dry weights recorded. In contrast, in a non-destructive sampling, the plants remain undisturbed and almost unhurt, which allow repeatability of observation. In plant ecological studies, the methods generally followed are: i) quadrat method, ii) transect method, iii) plot-less or point method, and iv) loop method (Das 2008). But, mostly, a quadrat is used for sampling in weed research. A quadrat of different sizes such as 20 cm x 20 cm, 50 cm x 50 cm, 100 cm x 100 cm (Rew and Cousens 2000; Salaudeen *et al.* 2022) may be used, depending on plants/ vegetation and magnitude of area of survey. A square quadrat may be useful in cropped lands, while a rectangular quadrat (100 cm x 50 cm) may be better in grasslands. For small plants like mosses, lichens and liverworts growing in patches, small quadrats of 20 cm x 20 cm; in grassland 50 cm x 50 cm quadrat if the stand is relatively pure, or 100 cm x 100 cm or more if greater diversity exists, may be quite useful. Generally, quadrats of 100 cm x 100 cm are used for studying herbaceous and weed vegetation in large areas like block/district. In forests the quadrat may be quite large from 10 m x 10 m to even one-fifth of an acre.

Minimum size and number of quadrats

Using large quadrat for survey usually results in greater accuracy, but is cumbersome and time-consuming. Therefore, before conducting sampling, a representative “minimum size of quadrat”, and a representative “minimum number of quadrat” are to be determined judiciously by “species-area curve” method (Das 2008). This may lead to ensure that the total sampling area and weed flora distribution in the sampled area are quite representative to the whole area of survey.

Sampling methods/techniques

The arrangement/placing of quadrats assumes enough significance in a survey. A definite method needs to be adopted for sampling based on types of vegetation and total area of vegetation. The methods could be representative method, random method, systematic method, restricted random sampling and stratified sampling (Das, 2008).

Crops/sites/fields of surveys

Random method is employed to select the sites. In each site, representative areas like crop fields, fencerows, ditch banks, and wet spots may be considered for assessment. Surveyors may walk through fields in a random fashion to evaluate the severity level of weed infestation, which may be rated using 1 to 5 scale (1: light infestation; 5: heavy infestation), or through qualitative descriptors such as low, medium, and high.

Time of sampling, data collection and analysis

A survey may have different purposes/objectives. It can be undertaken in crops seasonally (tropical climate), annually (temperate climate), or at certain intervals with specific objectives. The repetition of survey after a medium (5 years) or long (10 years and more) period may reveal weed succession/shift, similarity and dissimilarity of weed species over the years across the sites. The time of sampling is usually based on the chosen survey conditions. It could be at maximum ground cover of crop, completion of all management practices or maximum homogeneity of field conditions during flowering and seeding of the crop. Seasonal characteristics of weeds explain the variation more clearly even within same crop than by any other management or environmental parameter (Pinke *et al.* 2010).

Global positioning system (GPS) technology may give precise geographical location of weed infestations, facilitating spatial analysis and mapping. Digital data collection tools, such as mobile phones/smartphones allow for efficient recording and storage of field observations. Photography may serve as a visual record to document the extent and severity of weed infestations. Additionally, biomass sampling is conducted to quantify weed biomass, offering valuable insights into weed competition and the effectiveness of control measures.

Descriptive statistics (mean, median, mode, standard deviation, percentiles) are used to summarize data on weed density, frequency, and other attributes. Trend analysis for time-series data can assess weed species changes over time. Several linear and unimodal models (Table 6) may help to find

out relationships between weed populations, environmental factors, and management practices through indirect and direct gradient analysis (Hanzlik and Gerowitt 2016). Indirect gradient analysis using principal component analysis (PCA), correspondence analysis (CA), detrended correspondence analysis (DCA), and direct gradient analysis using redundancy analysis (RDA), canonical correspondence analysis (CCA), detrended canonical correspondence (DCCA) are being adopted by weed researchers for studying phytosociological aspects of weeds. Regression analysis can model and predict future weed infestation based on existing data. Further, spatial analysis allows for the mapping of weed distribution and identification of infested areas, supporting targeted management strategies (Tiwari *et al.* 2024).

Phytosociological study and importance value index (IVI)

The importance value index (IVI) gives an overall ecological importance of a weed/plant species in a community (Phillips 1959). It is calculated (Eq. 16) by summing up relative frequency (Rf), relative density (Rdn), and relative dominance (Rdo) of a species (Das 2008). Frequency, density, abundance, and dominance/cover are quantitative estimates, but individually they can hardly reveal the true ecological importance of a species in any plant community, which is normally heterogeneous in nature. Thus, IVI is calculated as a value out of 300 for each species and the species are arranged in decreasing order of IVI. Generally higher the IVI of a species, greater is its importance ecologically at a given place at that point of time and *vice-versa*. Summed dominance ratio (SDR) is half the value of importance value index (IVI).

$$IVI = (R_f + R_{dn} + R_{do}) \quad (16)$$

WEED DIVERSITY, RICHNESS, AND SIMILARITY/DISSIMILARITY STUDIES

A variety of methods are available for assessing weed diversity, each offering distinct advantages and limitations (Wilson *et al.* 1999; Yorks and Dabydeen 1998). Weed diversity can be evaluated at both the intra-community level [α (alpha) diversity] and inter-community level [β (beta) diversity] using the following indices (Nkoa *et al.* 2015)

Table 6. Common ordination methods with their properties and statistical assumptions (Hanzlik and Gerowitt 2016)

	Indirect gradient analysis	Direct gradient analysis
Linear model	Principal component analysis (PCA)	Redundancy analysis (RDA)
Unimodal model	Correspondence analysis (CA)	Canonical correspondence analysis (CCA)
	Detrended correspondence analysis (DCA)	Detrended canonical correspondence Analysis (DCCA)

Alpha (α) diversity (intra-community/within community)

Among the commonly used indices for measuring alpha diversity are Margalef's Diversity Index (DMg), Shannon–Weiner Diversity Index (H), and Simpson's Dominance Index (D). Margalef's Diversity Index provides a rapid estimate of species diversity based solely on species richness, though it is notably sensitive to sampling parameters such as unit, size, and design. In contrast, the Shannon–Weiner Diversity Index (H') incorporates both species richness and evenness in its calculation (Magnussen and Boyle 1995), and demonstrates moderate sensitivity to variations in sampling methodology (Eq.17). Diversity index generally indicates richness (number) of weed species in an ecosystem.

$$\text{Shannon-Weiner index (H')} = [-\sum_{i=1}^S \{pi(\ln pi)\}] \quad (17)$$

Simpson's Dominance Index (D) is primarily employed to quantify species dominance. While it is relatively insensitive to sample size, it does not account for species richness. Nonetheless, it can be utilized to describe species evenness (Eq. 18), offering insight into the degree to which a single species dominates a community.

$$\text{Simpson index (D)} = [1 - (\sum_{i=1}^S pi^2)] \quad (18)$$

Species evenness can also be derived from the values of Shannon–Weiner Diversity Index (H2), which reflects the uniformity or disparity in the distribution of weed species within a given system (Eq. 19).

$$\text{Evenness index (E)} = \left(\frac{H'}{\ln S} \right) \quad (19)$$

Species richness refers to the total number of distinct groups of individuals that are genetically or functionally related within a community (Eq. 20).

$$\text{Richness index (R)} = \left(\frac{S-1}{\ln N} \right) \quad (20)$$

Ecological dominance (Eq. 21) serves as an alternative measure to Simpson's Index and similarly indicates the extent to which a single species exerts dominance within an ecological system.

$$\text{Ecological dominance (C)} = \left[\sum_{i=1}^S \frac{ni(ni-1)}{N(N-1)} \right] \quad (21)$$

Where, S is the species richness i.e. the number of species presents in the quadrat, pi is the proportion of i^{th} species and $pi = ni/N$, ni is the density of i^{th} species, and N total number of individuals of all species in the treatment, “ is sum of all the factors.

Beta (β) diversity (inter-community/between the communities)

To compare differences or similarities between landscapes, two commonly used indices are Sørensen and Steinhaus Coefficients (Sørensen 1948). The Sørensen Coefficient/Similarity Index (Eq. 22) is a similarity measure based on species composition. It considers the number of species shared between communities relative to the total number of species present. In contrast, the Steinhaus Coefficient Index (Eq. 23) incorporates species abundance into its calculation. It estimates similarity by identifying the minimum abundance of each species shared between communities and expressing it as a proportion of the average total abundance across those communities.

$$\text{Sørensen coefficient index (Ss)} = \left[\left(\frac{2J}{a+b} \right) \times 100 \right] \quad (22)$$

where, J=the number of species common to each community; and (a+b) = the sum of the total number of species in each community.

$$\text{Steinhaus coefficient index (SA)} = \left(\frac{2W}{A+B} \right) \quad (23)$$

where: W =the sum of the lower of the two abundances of each species in the community; A =total number of individuals in population A; and B=total number of individuals in population B.

DETERMINATION OF WEED ECONOMIC THRESHOLD

The economic threshold (ET) is one of the major decision-making frameworks for rationalizing herbicides use for better weed management while reducing environmental impacts (Das *et al.* 2021). The ET is the density of a weed at which the cost of controlling it equals to the benefits obtained due to its control. It rejects complete eradication of weeds and advocates regulating weed populations at economically optimum levels. Several decision-making models on ET are available with high to low degree of precision (Cousens 1985a and 1985b; Kropff and Spitters 1991; Kropff and Lotz 1993). Several researchers have determined ET of single weed species having abundance in a crop (Moorthy and Das 1998; Hazra *et al.* 2011; Dodamani and Das 2013; Das *et al.* 2014; Raj *et al.* 2020; Das *et al.* 2021). However, the adoption of ET models as the major criterion for cost-effective herbicide use is low due to several reasons like seed bank build up by residual weeds, complexity in estimating ET density, patchy weed distribution, and limited validity in cropping systems with multiple weed species. From

the viewpoint of farmers, risk mitigation is more important than profit maximization, and the farmers are likely to take control actions at weed populations lower than the ET level (Coble and Mortensen 1992). But, the ET-based decision has great potential in designing weed management under single weed dominance in crops. Information on weeds population dynamics in cropping systems, biology, ecology and spatial heterogeneity would make ET more reliable, and managing weeds using integrated approach more successful. The density per unit area (Cousens 1985a and 1985b) and relative leaf area (Kropff and Spitters 1991; Kropff and Lotz 1993) of an individual weed are usually considered for working out its ET in certain crop. However, ET based on composite weed populations in crop fields hardly exists. The non-uniformity in weed species and their densities makes it difficult to determine whether the threshold reached or exceeded in crop field. There are a number of weed competition thresholds (Das 2008): i) period threshold, ii) quantity/ density threshold (damage threshold, economic threshold and action threshold). Kasasian and Seeyave (1969) have made a general assumption, such as, first 1/4th to 1/3rd period of the total growing duration/life cycle of a crop as its period threshold/critical period of weed interference. Another threshold, ecological threshold emphasizes on managing a composite culture of weeds to the level that maintains the existing plant species diversity and ecological harmony in a given area but hardly exists. In simpler terms, ecological threshold avoids the complete destruction/removal weeds or other vegetation from cropped or non-cropped situations.

HERBICIDE BIO-EFFICACY, PHYTOTOXICITY, AND IMPACT STUDIES

Herbicide, nano herbicide, and bioherbicide/ organic herbicides

The population, fresh weight, and dry weight of weeds, and the phytotoxicity, growth and yield of crop are invariably studied for assessing the bio-efficacy of herbicides. Weed population varies largely in fields (Brar *et al.* 2000; Kurchania *et al.* 2000) due

to non-uniform/ patchy/ erratic distribution of weeds across the plots and even within a plot. Similar justification applies to uneven distribution of fresh weight and dry weight of weed samples across the plots/ treatments. Fresh weight is generally considered less reliable than dry weight (Das 2001b). Dry weight, on the contrary, gives a better estimate of the dry matter accumulation in plants over times. This holds most reliable where the samples are homogeneous and constituted of mostly alive/ green plants (e.g. crop plants). But, in case of weeds, different kinds/ species of weeds present at different densities and different stages of growth usually show differential tolerance/sensitivity to the applied herbicide, which leads to graded injury symptoms at different stages of mortality, such as, some weeds would be completely dried/dead, some started drying, some are yellow or burnt and some are still alive/ green. But, weeds are usually sampled, irrespective of these injury effects, and fresh weight and/or dry weight recorded, which overshadow the variation. The injury-level variation is much overlooked, if only one parameter (either fresh weight or dry weight) is recorded. Again, the variation in weed density distribution across the plots may magnify the sampling error. In such situation, lower the dry weight of weeds, greater is the bio-efficacy of treated herbicide – does not always hold true. Therefore, the reliability/ authenticity of weed fresh weight and/or dry weight data depicting herbicide bio-efficacy were evaluated by introducing two new parameters (Eq. 24, 25 & 26), such as, fresh weight (Fw): dry weight (Dw), and moisture content (%) of the weed samples fresh weight-basis or dry weight-basis (Das 2001b), and the bio-efficacy of herbicides, namely, post-emergent foliage-active glufosinate-ammonium and glyphosate each at 2.5 and 3.0 L/ha (product) was precisely estimated on *Cynodon dactylon* and *Cyperus rotundus* (Table 7). Similar analysis by Das and Yaduraju (2002) was also done on fixed area basis and fixed fresh weight basis. These two new parameters (Fw:Dw; moisture content) could separate out the usual variation of weeds across the plots and were quite reliable/ responsive and highly aligned to visual observations. They delivered the

Table 7. Bio-efficacy of glufosinate-ammonium and glyphosate on *Cyperus rotundus* at 20 days after treatment (part of the table 1 of Das 2001b)

Treatment	Product (L/ha)	<i>Cyperus rotundus</i>					
		Fresh weight (Fw) (g/m ²)	Dry weight (Dw) (g/m ²)	Fw-Dw (g/m ²)	Fw:Dw	Moisture (%) (Fw basis) (%)	Moisture (%) (Dw basis) (%)
Glufosinate-AM	2.5	114.0	85.1	28.9	1.34	25.4	33.9
Glufosinate-AM	3.0	95.4	75.3	20.1	1.27	21.1	26.7
Glyphosate	2.5	112.4	78.7	33.7	1.43	29.9	42.8
Glyphosate	3.0	93.2	68.8	24.4	1.35	26.2	35.5
Unweeded control	--	320.0	116.4	203.6	2.75	63.6	174.9

truth when the result remained inconclusive based on fresh weight and dry weight of the weed sample. They, therefore, may be adopted along with fresh weight and dry weight for better appraisal of the bio-efficacy of herbicides, nano herbicide, and bioherbicide/organic herbicides.

$$\text{Fw: Dw} = \frac{\text{Fresh weight of weed sample}}{\text{Dry weight of weed sample}} \quad (24)$$

$$\text{Moisture (\%)} (\text{Fw basis}) = \frac{(\text{Weed fresh weight} - \text{weed dry weight})}{\text{Weed fresh weight}} \times 100 \quad (25)$$

$$\text{Moisture (\%)} (\text{Dw basis}) = \frac{(\text{Weed fresh weight} - \text{weed dry weight})}{\text{Weed dry weight}} \times 100 \quad (26)$$

Nano-herbicide formulations have higher ability for controlled release, lower decomposition rate, and improved bioavailability through targeted delivery. They have become exceedingly important in recent years towards achieving higher weed control efficiency with no or negligible residue and environmental footprints. The bio-efficacy of nano-herbicides/organic herbicides can be evaluated from crop fields in a similar way as mentioned above for herbicides. The weed control efficiency of conventional high molecular weight herbicides may be influenced tremendously under higher temperature and atmospheric carbon dioxide concentration, and the nano-herbicides may take their place in the coming years. The altered growth, physiology and tolerance levels of weeds may show lower susceptibility to herbicides with a consequent change in effectiveness and metabolism/degradation of herbicide in the environment. Many perennial weeds exhibit deep and persistent root system, high phenotypic plasticity, allowing them to adjust their growth and reproductive strategies in response to elevated atmospheric CO₂ levels and temperature. Such weeds allocate more resources to underground vegetative parts that acts as a food reserve to survive under unfavorable situations, while they have capability to regenerate abruptly once favorable conditions prevailed. Nano-formulated herbicides can be engineered for controlled release and improved mobility, allowing them to penetrate deeper into the soil profile and reach underground structures such as *Cyperus* spp tubers more effectively than conventional herbicides (Kah *et al.* 2012). This improves the bioavailability and persistence of active ingredients near critical target zones, enhancing control of regenerating propagules in perennial species. Nano herbicides have potential for integration into modern spraying tools like UAVs, especially in precision agriculture. Nano herbicides research may focus on nanoparticles characterization

and quantification, their uptake, translocation, persistence, and bio-safety evaluation.

The so-called organic herbicides need rigorous field testing for their selectivity to crops/ crop tolerance before they are recommended for organic production systems, although equally applicable for inorganic production system. These herbicides have environmental safety owing to low persistence, reduced resistance risk owing to non-selective contact action and can be incorporated to regenerative production systems.

Assessment of crop phytotoxicity and weed control

Selective herbicide upon application at the recommended dose to a crop produces certain injury symptoms, mainly, on weeds, and in invisible, negligible, and undetectable scales on crop plants. The graded response of growth inhibition/reduction or death of crop plants due to herbicide is phytotoxicity. The level of phytotoxicity varies from plant to plant: weeds being most affected, whereas crop plants not affected or least/negligibly affected (particularly when herbicide is selective and applied at the recommended dose). Therefore, observations should be recorded separately for weeds and crop. Phytotoxicity to weeds indicates the degree of weed control (called bio-efficacy), whereas phytotoxicity to a crop indicates the degree of herbicide's selectivity to crop whether this herbicide can safely be used in that crop. The phytotoxic effects of herbicides can be assessed qualitatively by visual rating (**Table 8**) using a scale from 0 (zero) to 10 (where 0 equals to 0% and 10 equals to 100% phytotoxicity) or from 0 (zero) to 5 (where 0 equals to 0% and 5 equals to 100% phytotoxicity). Other phytotoxicity scales can be 1-5 or 1-10 as well. For recording phytotoxicity in the fields, first percent injury to crop compared to control is assessed visually and, then, rating is executed using these scales, such as, 0 for 0%, 1 for 10%, 2 for 20% injury and so on in the 0-10 scale. At least two persons, standing on either side of the herbicide-treated plot may be deputed for visual rating of phytotoxicity. These persons should be literate in weed science and have enough knowledge on the mode of action and usual injury symptoms of the specified herbicide. Per cent mean of phytotoxicity may be calculated simultaneously from the observations of both persons treatment-wise across replications in the field. A visual scoring of injury symptoms on crop due to herbicides was reported long back (Rao 1983). An exhaustive but convenient scoring of the phytotoxic effects on crops due to pre-emergence (PE) and post-emergence (PoE)

herbicides has been formulated here (**Table 8**). For PE herbicides, crop seed germination, seedlings emergence and population/stand may be considered as there is no direct contact/ exposure of herbicides with the crops. But, for PoE herbicides, crop seedlings death/mortality, chlorosis, necrosis, yellowing, bending, twisting and curling of leaves, growth stunting etc, which ultimately result in final plant stand may be considered. These symptoms are hardly uniform on all individual plants of the crop unless there is complete death of crop plants, rather they are graded/variable and difficult to quantify on individual plant-basis. Therefore, the phytotoxicity may be considered collectively on plant population-basis. For judging the phytotoxicity, the following steps may be followed:

- i) Wait for 5-10 days after application of herbicides for the injury symptom to be sufficiently visible for assessment depending on the chemical nature of the herbicides.
- ii) Two persons should stand on the middle of bund along the widths on either side of the treated plot and look at the whole plot along the length and assess the per cent of plot area or per cent plant population having injury from slight to severe scales.

iii) Similarly, they should stand on the middle of bund along the length on either side of the same treated plot and look at the whole plot along the width and assess the per cent of plot area or per cent plant population having injury from slight to severe scales.

iv) Count the injured plants row-wise or plot-wise arbitrarily and existing uninjured plant population to appraise the truth of visual rating.

v) In a crop having similar biochemical/physiological mechanisms, the judging of phytotoxicity on area-basis may be as good as the single plant-basis phytotoxicity evaluation involving the injuries on leaves, stems, branches of crop plants.

HERBICIDE RESIDUE AND ENVIRONMENTAL IMPACT ANALYSIS

Herbicide residue analysis in crop and soil

Herbicide residue studies focus on understanding its persistence, degradation, and environmental impact through field and lab experiments, using chromatography to measure residue levels in soil and crops. Degradation studies can analyze microbial and environmental factors, while predictive models assess risks like groundwater

Table 8. Visual rating of crop phytotoxicity/injury and weed control due to pre-emergence (PE) and post-emergence (PoE) herbicides in a 0-10 scale at 7-10 days after herbicide application

Crop phytotoxicity rating (compared to weed-free control)			Weed control rating (compared to weedy check control)		
Crop injury magnitude	Injury score	Injury symptoms on crops collectively plot-basis in the fields or whole plant-basis	Weed control magnitude	Weed control score	Injury symptoms on weeds collectively plot-basis in the fields or whole plant-basis
No injury	0	Normal; germination/seedlings emergence/crop plants stand completely unaffected (PE); Normal; no toxicity/injury to standing crop plants (PoE)	No weed control	0	No weed control; weed germination/emergence not at all affected (PE); No toxicity/injury to standing weeds (PoE)
Negligible	0.1-0.9	1-9% reduction in germination/seedlings emergence/crop plants stand (PE); 1-9% crop plants showing injury symptoms or 1-9% injury whole plant or whole plot basis (PoE)	Negligible/ less weed control	0.1-0.9	1-9% weed control considering reduction in weed germination/ emergence (PE); 1-9% weed control considering injury symptoms or 1-9% injury whole plant or whole plot basis (PoE)
Slight (perceptible injury)	1.0-3.9	10-39% reduction in germination/seedlings emergence/crop plants stand (PE); 10-39% crop plants showing injury symptoms or 10% injury whole plant or whole plot basis (PoE)	Moderate/ medium weed control	1.0-3.9	10-39% weed control considering reduction in weed germination/ emergence (PE); 10-39% weed control considering injury symptoms or 10-39% injury whole plant or whole plot basis (PoE)
Moderate (less chance of recovery)	4.0-6.9	40-69% reduction in germination/seedlings emergence/crop plants stand (PE); 40-69% crop plants showing injury symptoms or 40% injury whole plant or whole plot basis (PoE)	High weed control	4.0-6.9	40-69% weed control considering reduction in weed germination/ emergence (PE); 40-69% weed control considering injury symptoms or 40-69% injury whole plant or whole plot basis (PoE)
Severe (majority plant stand destroyed)	7.0-9.9	70-99% reduction in germination/seedlings emergence/crop plants stand (PE); 70-99% crop plants showing injury symptoms or 70% injury whole plant or whole plot basis (PoE)	Very high weed control	7.0-9.9	70-99% weed control considering reduction in weed germination/ emergence (PE); 70-99% weed control considering injury symptoms or 70-99% injury whole plant or whole plot basis (PoE)
Complete destruction	10.0	100% reduction in germination/seedlings emergence/crop plants stand (PE); 100% injury to crop plants, whole plant or whole plot basis (PoE)	Complete weed control	10.0	100% weed control considering reduction in weed germination/ emergence (PE); 100% weed control whole plant or whole plot basis (PoE)

contamination. Bioassay methods with sensitive indicator plants may be used for qualitative and quantitative estimation of herbicides residue, and GIS tools are used for spatial monitoring of residue patterns. These methodologies support safer and more sustainable herbicide use in weed management (Hasan *et al.* 2021; Parven *et al.* 2024). Gas chromatography (GC), often with capillary columns, is widely used (Tadeo and Sanchez 2000). Multi-residue methods (MRMs), which determine a wider range of multiclass pesticides are preferred over single residue methods because the products applied and the regularity of treatments are generally unknown and residues of more than one pesticide can be present in samples (Pico 2016). The complete procedure for determining pesticide residues in food, soil and environment is complex and consists of several stages, such as i) sample preparation, ii) extraction and clean up and iii) detection as per standard procedures (Raj *et al.* 2022). In the 2000's, several advanced methods were developed for detecting pesticides in food, focusing on rapid and simple pretreatment. Among them, the QuEChERS method (Quick, Easy, Cheap, Effective, Rugged, and Safe) became most popular (Pico 2016).

Herbicide impacts on soil health

Soil physical properties

The important soil physical properties such as soil aggregation, bulk density, penetration resistance, infiltration, soil temperature, moisture content, and porosity are influenced by weed control practices/herbicides (Raj *et al.* 2023). It is crucial to record observation on soil physical parameters under weed control experiments, and such experiment may be conducted/continued for a longer period. The soil bulk density (BD) can be determined by the core sampler method (Lal 2010). For soil aggregation study, soil samples may be collected randomly from five places in each treatment plot and analysed using Yoder apparatus (Yoder 1936). The collected soil samples in sieves may be classified as large macroaggregates (aggregates size >2000 μm), small macroaggregates (aggregates size 250-2000 μm), and microaggregates (aggregates size 53-250 μm). Other parameters such as mean weight diameter (MWD), geometric mean diameter (GMD) (Kemper and Rosenau 1986), and aggregate ratios (AR) of soils (Choudhury *et al.* 2014) may be also analysed.

Soil chemical properties

Soil pH, EC, available N, P and K

Soil pH can be measured using digital glass electrode pH meter (Jackson 1973). Electrical

conductivity (EC) is measured in 1:2.5 soil: water suspension using conductivity meter (Piper 1950). The available N may be estimated by alkaline KMnO_4 method (Subbiah and Asija 1956) in a Kjeldahl assembly, available P content by ascorbic acid method (Olsen *et al.* 1954) for alkaline soils and P-Bray 1 (0.03 M NH_4F and 0.025 M HCl) and P-Bray 2 method (0.03 M NH_4F + 0.1 M HCl) for acidic soils (FAO 2021). Available K may be determined using flame photometry after extraction with neutral normal ammonium acetate (Jackson 1973). Similarly, other macro-nutrients and micro-nutrients may be analysed.

Organic carbon and carbon pools

For total organic carbon content, soil samples should be finely ground and sieved (250 μm) and analysed using TOC dry combustion analyser. Walkley and Black carbon (WBC) content in soil samples are determined by Walkley and Black (1934) method using $\text{K}_2\text{Cr}_2\text{O}_7$ and conc. H_2SO_4 and ferrous ammonium sulphate in the presence of phosphoric acid and diphenylamine indicator. Different fractions of soil organic carbon of varying lability may be estimated following Walkley and Black (1934) method as modified by (Chan *et al.* 2001) using separately 5, 10 and 20 mL of concentrated (36 N) H_2SO_4 and 1 N $\text{K}_2\text{Cr}_2\text{O}_7$ solution. This results in three acid-aqueous solution ratios of 0.5:1, 1:1, and 2:1 that corresponded to 12, 18 and 24 N H_2SO_4 (WBC), respectively and produces different amounts of heat of reaction to bring about oxidation of SOC of different oxidizability. The amounts of C is determined allowed separation of total SOC into the following four fractions/pools of decreasing oxidizability (Chan *et al.* 2001):

Pool/fraction I (very labile): organic C oxidized with 12 N H_2SO_4 ;

Pool/fraction II (labile): the difference in organic C oxidized under 18 N and 12 N H_2SO_4 ;

Pool/fraction III (less labile): the difference in organic C oxidized under 24 N (WBC) and that under 18 N H_2SO_4 ;

Pool/fraction IV (non-labile): the difference between TOC and organic C oxidizable under 24 N H_2SO_4 .

Further, the four C fractions were classified under Active Pool ($C_{\text{fraction I}} + C_{\text{fraction II}}$) and Passive Pool ($C_{\text{fraction III}} + C_{\text{fraction IV}}$)

Soil biological properties

Enumeration of soil fungi and bacteria under herbicide/weed control treatments may be done by serial dilution and agar/pour plate techniques using a 1 ml soil solution for plating (Das *et al.* 2010). Martin Rose Bengal agar medium (Martin 1950) for fungi and soil extract nutrient agar medium (Allen 1953) for bacteria are used. Nematode populations may be determined as per Southey (1986). Besides, microbial activity can be measured in terms of microbial biomass carbon (MBC), dehydrogenase activity (DHA) and alkaline/acid phosphatase activity from

different soil depth at flowering stages of crops. Soil samples are to be collected in small polythene bags by soil auger from each plot of the experimental field. Soil microbial biomass carbon is estimated as per Vance *et al.* (1987) and dehydrogenase activity as per Casida *et al.* (1964).

Weed control treatments/ herbicides impact on greenhouse gases (GHGs) emission and C-footprints

Weed control treatments impact on GHGs emission and C-footprints need to be properly estimated for knowing the implication of agri-practices on climate change and global warming. Herbicide, hand weeding, inter-culture operations, hoeing etc. have impacts on GHGs emission (West and Marland 2002; Lal 2004) and environmental footprints (Table 9). The GHGs may be collected and sampled using a closed chamber technique and accordingly analysed (Bhatia *et al.* 2004, Gupta *et al.* 2016).

WEED DETECTION, MAPPING, AND PRECISION CONTROL

Weed detection involves identifying and distinguishing weeds from crops or other vegetation using sensing technologies, image analysis, and pattern recognition algorithms to support efficient weed management in agricultural systems. It integrates optical, spectral, or thermal sensors with machine learning (ML) and computer vision techniques to capture and interpret spatial and temporal weed data, enabling targeted weed control in precision agriculture. Weed detection is challenging because weeds and crops often exhibit similar colour and texture characteristics. Traditional ML algorithms such as Support Vector Machine (SVM), Random Forest (RF), and k-Nearest Neighbour (k-NN) have been widely used for weed classification, achieving

about 90–97% accuracy (Hashemi-Beni *et al.* 2022). Recently, deep learning (DL) approaches, particularly Convolutional Neural Networks (CNNs), have gained prominence due to their ability to extract complex spatial features from images for improved weed identification (Wu *et al.* 2021).

Steps for precision weed management using AI-based deep learning

Data acquisition

The weed detection pipeline begins with data acquisition, where image data are collected using unmanned aerial vehicles (UAVs), ground robots, handheld sensors, or satellite platforms (Figure 4). UAVs commonly capture RGB, multispectral, hyperspectral, or thermal imagery at 2–20 m altitude with resolutions around 3000 × 4000 pixels, while robots such as BoniRob collect multispectral imagery and satellites provide 4-band (RGB + NIR) data for large-scale monitoring. Two sensing approaches are commonly used: proximal sensing, where sensors mounted on tractors or robots collect high-resolution images using architectures such as GoogleNet, VGGNet, and DetectNet, and remote sensing, where UAVs or satellites collect imagery for large-area weed monitoring using CNN, DNN, or Fully Convolutional Network (FCN) models.

Dataset preparation and image pre-processing

It is performed through image resizing, colour model conversion, annotation, and augmentation techniques such as rotation, flipping, noise injection, and colour transformation, which increase dataset diversity and improve model training. This is followed by image preprocessing, which includes radiometric correction (illumination and sensor noise), geometric correction (spatial alignment), orthomosaic generation, and background removal. Vegetation

Table 9. Weed management and ecological footprint (West and Marland 2002, Lal 2004)

Weed management Practice	Carbon emissions (kg CO ₂ e/ha)	Description	Advantages	Disadvantages
Manual weeding	5–20	Labor-intensive removal using hand tools	Low emissions, no chemicals	High labor cost, not feasible for large areas
Mechanical weeding	50–150	Use of tractor-drawn or power tiller implements	Reduces labor, efficient in row crops	Fuel use increases emissions, soil disturbance
Chemical weeding (herbicides)	150–300	Application of synthetic herbicides (e.g., glyphosate, atrazine)	Quick, cost-effective	High emissions from manufacture & application
Mulching (organic/plastic)	20–100	Weed suppression through cover materials	Reduces soil evaporation, moderate emissions	Plastic mulch adds disposal burden
Cover cropping	10–50	Use of dense-growing crops to outcompete weeds	Sequesters carbon, improves soil health	May require termination using herbicides or tillage
Flame weeding	300–600	Use of propane burners to kill weeds	Non-chemical, useful in organic systems	Very high fuel use and emissions
Integrated weed management	70–200	Combines cultural, mechanical, and chemical control	Balanced approach, moderate emissions	Requires knowledge & planning

indices such as NDVI, NDRE, and SAVI are commonly applied to separate vegetation from soil and enhance weed detection.

Analysis using AI/ML

The processed imagery is then analysed using ML and DL classifiers to distinguish weeds from crops and background vegetation. CNN-based architectures such as ResNet, U-Net, and YOLO variants are widely used. For example, YOLOv7 (CSCW-YOLOv7) achieved 94.4–98% mean average precision for weed detection in wheat (Wang *et al.* 2024), while a dilated CNN achieved 94% accuracy using 15,000 soybean and broadleaf weed images (Tripathi *et al.* 2025). Detection approaches include bounding-box detection, semantic segmentation, and instance segmentation (Genze *et al.* 2022). Semantic segmentation models such as U-Net, SegNet, and DeepLabV3+ classify each pixel as weed, crop, or soil, whereas instance segmentation models such as Mask R-CNN, YOLACT, SOLO, and CenterMask identify individual weeds even under overlapping conditions, enabling weed density and biomass estimation.

Model evaluation

Model performance is evaluated using accuracy, F1-score, mean absolute error (MAE), and root mean square error (RMSE). Several architectures including DNN (You *et al.* 2020), DeepSolanum-Net (Wang *et al.* 2021), ERFNet-based Bonnet (Su *et al.* 2021), Modified U-Net (Zou *et al.* 2021a, 2021b), ResNet-34 (Zhang *et al.* 2022), DeepLabv3+ (Hashemi-Beni *et al.* 2022), and Mask R-CNN (Sapkota *et al.* 2022) have been widely applied, often using transfer learning to improve performance with limited datasets (Rai and Sun 2024).

Weed mapping

After classification, weed mapping is performed to analyse spatial and temporal weed distribution, density, and species composition. The model outputs are converted into georeferenced raster or vector layers using GIS software such as QGIS or ArcGIS, and spatial interpolation methods such as kriging or inverse distance weighting (IDW) are used to identify weed hotspots (Wang *et al.* 2024). Repeated UAV flights enable temporal weed monitoring, helping evaluate weed emergence patterns and herbicide effectiveness. These maps are integrated into decision support systems to generate prescription maps for site-specific weed management. Ultra-high-resolution UAV imagery combined with object-based image analysis (OBIA) further enhances accurate in-season weed mapping. The steps in weed detection,

weed mapping, and site-specific herbicide sprays using UAVs/ robots or variable rate applicators (VRA), are orderly mentioned below (**Figure 4**):

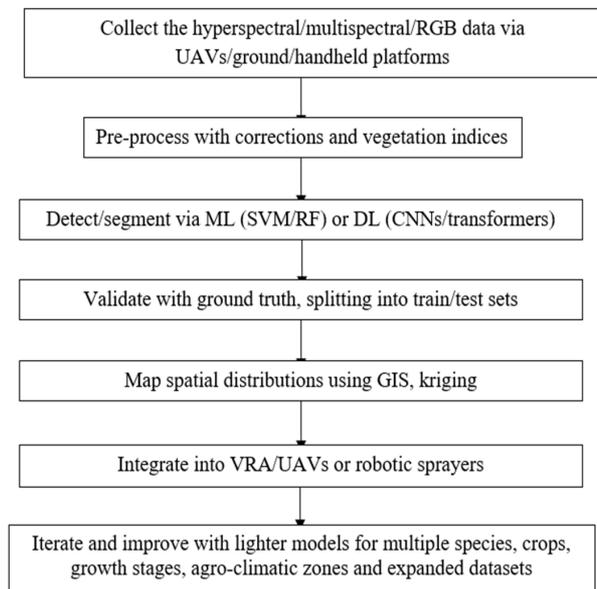


Figure 4. Steps in weed detection, mapping and precision weed management

Precision spraying technique

The final implementation phase i.e., precision weed control is implemented using AI-enabled UAVs, robotic weeders, and variable rate applicators (VRA) integrated with GPS and high-resolution sensors for targeted herbicide application. Common UAV platforms include DJI Matrice 100, DJI Agras MG-1, Sentra P.H.X., eBee SQ Fly, and AgEagle RX-60, which can cover approximately 400–600 acres within 40–55 minutes (Meesaragandla *et al.* 2024). Field trials in a 25 ha sugarcane field in Queensland, Australia, demonstrated that UAV-based spot spraying achieved about 97% weed control while reducing herbicide use by 35% compared with broadcast spraying (Azghadi *et al.* 2025). There are various factors that can affect the efficiency of this particular method of aerial spraying as follows:

- There should be definite altitude (1.5-3.0 m above canopy) and velocity (11-18 km/h) of the spraying operation.
- Suitable weather conditions like wind (1-3 m/s), temperature (15-28°C), humidity (>60%) at the time of application.
- Design and performance of the droplet-generating equipment, i.e., flat fan nozzle (150-250 µm drop size is suitable, lower size may drift and higher may bounce off).
- Application rate of the spray solution (15-25 liters/ha; 30-50 droplets/m²). The spray concentration is higher (70-80% water: 20-30% chemical) than traditional high-volume sprays (98% water:2% chemical).
- Physical and chemical properties of the spray formulation, i.e., size, polarity, anti-drift agents, anti-

evaporation agents, and surfactants etc. Suspension concentrate (SC), emulsion in water (EW), and oil dispersion (OD) are generally preferred formulation over wetttable powder (WP).

- Thickness of the crop: Grassy crops with erect leaves are easier to penetrate but broad-leaved crops require higher downwash or smaller droplets.

Therefore, UAVs-based weed detection using advanced sensing, image analysis, and DL enables accurate, site-specific weed monitoring and a data-driven management in precision agriculture. These innovations reduce input costs, labor, and environmental impact while improving overall crop health and productivity. Continued improvements in real-time processing, model generalization, and automated spraying systems will further enhance the scalability and effectiveness of precision weed control.

Conclusions

Weed interference is a collective impact of different weed species. Weeds change continuously in crop field ecosystems, and more so under the changing climate. Therefore, the appraisal mechanisms of weed interference and dynamics, weed control efficiency, economic threshold, and herbicides bio-efficacy, selectivity and weed control spectrum need to be renewed/ reoriented to keep pace with the current changing scenarios with more scientific-bias. Weed science to become a distinct branch of biological sciences should have certain self-generated/ self-governed concepts, principles and hypotheses, defined/robust treatments, sound science-based methodologies, standard field plot and statistical techniques. Some theories/ principles/ advances of basic sciences (biology, ecology, physics, chemistry, mathematics) need to be put into use in weed science for developing inter-disciplinary linkage and widening the horizon of weed science. Finally, weed science should be developed as a basic science, an applied science, and more appropriately an interdisciplinary science with constant/ continuous research thrust towards improving methodologies.

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RESEARCH ARTICLE

An estimate of the potential impact of integrated weed management technologies on major field crops productivity and economic gains in India

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ABSTRACT

Weeds remain one of the most pervasive biotic constraints to crop productivity in India, causing substantial yield and economic losses across diverse cropping systems. This study aimed to estimate the potential contribution of integrated weed management (IWM) interventions to the production of major field crops in India and the possible economic gains resulting from these interventions. Weed management was estimated to be implemented in over 125.33 million hectares, representing about 67% of the total cropped area under major cereals, pulses, oilseeds and commercial crops (187.06 million hectares). Adoption of IWM interventions was estimated to result in an additional 96.62 million tonnes of crop production annually with an estimated economic returns of ₹ 1.89 trillion. The largest share of gains was estimated to be by cereals due to their extensive area coverage, with a contribution of 45.78 million tonnes of additional output which is over half of the total economic benefits. Commercial crops, particularly sugarcane and potato, generated disproportionately high production gains despite relatively less cultivated acreage, reflecting their high per-unit productivity and responsiveness to IWM. Oilseeds and pulses were estimated to have moderate absolute gains, constrained mainly due to lower adoption of IWM. Overall, the findings of this estimate demonstrate that scaling of timely IWM can substantially narrow yield gaps improve farm profitability, underscoring its central role in sustainable agricultural intensification.

Keywords: Crop productivity, Economic returns, India, Integrated weed management

INTRODUCTION

Indian agriculture remains the backbone of the national economy, contributing approximately 18.4% to Gross Value Added in 2024–25 and supporting nearly 46.1% of the population (DESE 2025). The sector has shown remarkable resilience, with total food grain production reaching a record 357.73 million tonnes in the 2024–25 crop year, an 8% increase over the previous year, driven by peak yields in staples such as rice and wheat, ensuring self-sufficiency and stabilizing domestic food availability (PIB 2025). Despite these gains, the sector faces major bottlenecks, including shrinking landholdings, stagnating factor productivity, climate variability, declining soil health, water scarcity, and significant yield losses due to biotic stresses such as weeds, insect-pests, and diseases. Among these, weed competition alone accounts for 37% yield losses in major crops, representing the single largest biotic constraint to food grain productivity (Mishra *et al.* 2024). Farmers do adopt some form of weed management (partial weed management) in their

crops, depending on their socio-economic status, knowledge, and availability of resources. Gharde *et al.* (2018) estimated that weeds caused an average yield loss of 25% (13% in transplanted rice to 36% in groundnut) under farmers' level of weed management, valued at USD 11 billion annually in ten major field crops of India. There is a need to reduce these losses, and substantial improvements in the production of agricultural field crops could be achieved if yield losses are further reduced by following improved IWM practices (Rao *et al.* 2017; Rao 2022).

Weed management in agro-ecosystems in India is a critical challenge for enhancing crop productivity, as weeds have been reported to cause potential yield losses of 33% to 80% across major field crops (Rao *et al.* 2007). The shift in weed flora and rapid evolution of herbicide resistance, particularly in *Phalaris minor* within the rice-wheat cropping systems (Choudhary and Mishra 2023), *Echinochloa crus-galli* and *Cyperus difformis* in rice (Choudhary *et al.* 2021; 2023) and *Echinochloa colona* in soybean (Chander *et al.* 2023); severe labour shortages and rising wages (Rao *et al.* 2020); weed-crop dynamics altered by climate change (Chauhan 2020) have made weed management more critical in

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enhancing crop production in agro-ecosystems. To address these issues, the adoption of integrated weed management (IWM) strategies was suggested (Rao and Nagamani 2010). IWM technology was developed and has been proven to successfully bridge the crop yield gap, thus enhancing crop productivity (Singh and Singh 2020; Choudhary *et al.* 2022; Dubey *et al.* 2023; Rao and Korres 2024). However, the adoption of IWM in India remains low due to lack of technical knowledge regarding precise herbicide application and limited access to specialized mechanization (Gharde and Singh 2021).

The IWM technologies were proven to significantly improve the farm productivity and profitability in Indian agriculture compared with conventional weed control (farmer's practices), due to superior weed suppression and efficient input use. Thus, this study hypothesizes that regional variation in yield and economic gains is driven by differences in IWM adoption and area coverage. This study was conducted with an objective to estimate the potential contribution of IWM interventions to major Indian crops production and to economic gains. In this assessment, we have: (i) assessed the status of weed management in India with respect to area coverage and adoption levels; (ii) quantified yield gains in major field crops with the adoption of IWM; (iii) estimated the economic benefits; and concluded by identifying constraints and opportunities for scaling up IWM adoption in India.

MATERIALS AND METHODS

The data source

The study was based on the detailed data collected from national and state-level institutional/organisational sources, including the Directorate of Economics and Statistics (DES), Ministry of Agriculture & Farmers' Welfare, ICAR research reports, AICRP on Weed Management, published literature, and government databases. The data, from the sources mentioned, on major food grain and commercial crops across key agro-ecological regions of India was used for this study.

Assessment of IWM coverage and adoption area

Data on crop-wise acreage under different weed management practices (manual, mechanical, chemical, and IWM) were collected with the help of AICRP on weed management centres, herbicide industries, personal communication with state department of agriculture, KVKs, NGOs, *etc.* across the country (detailed data with authors, unpublished) and the summary of collected data was compiled.

Similarly, the herbicide consumption data were also collected from various states of India and used to estimate the area under herbicide use (detailed data with authors, unpublished). The percentage adoption of weed management was estimated by relating the area under weed management to total cropped area for each crop across the country. Area coverage under IWM (*e.g.* ≥ 2 complementary weed control practices) was estimated, and then stratified farmer surveys were conducted across major crop-growing regions to determine the proportion of land where multiple weed control practices are used. These proportions were extrapolated to total crop area using area-weighted expansion and separated with secondary sources such as extension records and input-use data. The synthesized estimates underwent internal consistency screening, outlier checks, and expert validation to enhance methodological robustness and reliability.

The estimation of crop yield gain due to IWM

The data on different crop grain yields with IWM and conventional or farmer-managed weed control practices, as reported in multi-location trials and on-farm studies, were pooled, compiled, and used to estimate the crop yield gains due to the adopted weed management practices. The crops yield gain was compared with the National average productivity of different field crops.

Economic analysis

The economic advantages due to the adoption of weed management practices was assessed using minimum support price and market rates (₹/ton) of each of the crop for the year 2024-25 (rice: 23,000, maize: 22,250, jowar: 33,710, bajra: 26,250, ragi: 42,600, other minor millets: 35,000, wheat: 24,250 and barley: 24,250, pigeonpea: 75,500, blackgram: 74,000, greengram: 86,820, lentil: 67,000, chickpea: 56,500, other pulses: 52,000, groundnut: 67,830, castor: 45,000, sesame: 92,670, niger: 87,170, soybean: 48,920, sunflower: 72,800, rapeseed and mustard: 59,500, linseed: 55,000 and safflower: 59,400, sugarcane: 3,400, cotton: 71,210 and potato: 15,000). The incremental economic gains attributable to IWM were calculated based on additional crop yield and additional cost due to the adopted weed management practice.

Data analysis

The descriptive statistics and comparative analyses were used to evaluate the adoption trends, yield advantage, and economic benefits across the crops considered for this study.

RESULTS AND DISCUSSION

Previous studies indicate that limited adoption of timely weed management remains a major constraint in several crops in India, despite their high relative yield responsiveness to improved weed management (Choudhary *et al.* 2022, Kumar *et al.* 2022). The estimated weed management coverage and improved crop productivity and economic returns as observed in this assessment study are discussed here.

Cereals

The major cereal crops considered for this study were rice, maize, jowar, bajra, ragi, other millets, wheat and barley. The estimates made by this study indicated substantial crop-wise gains in productivity, total production, and economic gains due to the weed management interventions across major cereals and millets in India (**Table 1**). Out of the total cultivated area of 109.83 million hectares under cereal crops, nearly 81.45 million hectares were under some form of weed management. The estimated average production gain due to the practiced IWM ranged between 150 kg/ha in millets to 1000 kg/ha in maize, which was estimated to result in 4.75% to 27.68% increase in yield over the national average productivity with an additional food grain production of 45.78 million tonnes. These findings align with earlier estimates that weeds alone account for 25–40% yield losses in cereals under farmers' field conditions, underscoring the importance of weed management as a critical yield-enhancing intervention (Chauhan *et al.* 2012, Rao and Chauhan 2015).

Effective weed control in rice systems, particularly under transplanted and direct-seeded conditions, has been shown to increase yields by 15–35% by reducing early-season competition for nutrients, water, and light (Choudhary *et al.* 2025a). Similarly, in wheat, unchecked infestation of grasses

and broad-leaved weeds can reduce yields by 30–50%, making weed management a key determinant of profitability (Singh *et al.* 2016). In this study, rice and wheat accounted for the largest absolute gains, largely due to their extensive area coverage and dominance in national food grain production. Rice contributed nearly 20.0 million tonnes of estimated additional production with the highest economic return (₹ 459,865 million) and wheat with 14.78 million tonnes and ₹ 358,371 million.

Maize recorded the highest estimated relative yield response, with an average gain of 1,000 kg/ha, representing a 27.86% increase over the national mean yield. This translated into an additional 10.40 million tonnes of production and ₹ 231,361 million in economic returns. The strong response of maize reflects its high sensitivity to weed competition during the early growth period. Although coarse cereals and millets showed lower estimated absolute gains due to smaller area coverage, relative yield improvements were notable, with increases of 16.13% in jowar, 13.13% in bajra, and 14.99% in millets. These observations highlight the potential of weed management to enhance productivity in rainfed and marginal environments where millets are predominantly grown (Dubey *et al.* 2023). Overall, the findings of this study confirm that improved weed management could be a high-returns potential strategy for bridging yield gaps and enhancing national food grain production without expanding cultivated area.

Pulses

Weeds were reported to cause 30–80% yield losses in pulses due to their slow initial growth and weak competitive ability (Kumar *et al.* 2022, Mishra and Choudhary 2026). Across major pulse crops, weed management interventions estimated to be

Table 1. The estimated weed management coverage and its impact on productivity and economic returns of major cereals and millets in India (2024-25)

Crop	Area (mha)	Production (mt)	Productivity (kg/ha)	Estimated area under weed management (mha)	Estimated % of area coverage under weed management	Estimated crop productivity gain (kg/ha) due to IWM	Estimated % increase in yield over national average	Estimated additional crop production due to IWM (mt)	Estimated additional gains in economic return (Rs in million)
Rice	51.27	150.18	2929	39.99	78	500	17.07	19.99	459,865
Maize	12.09	43.41	3590	10.40	86	1000	27.86	10.40	231,361
Jowar	4.00	4.96	1240	1.20	30	200	16.13	0.24	8,080
Bajra	7.36	11.21	1523	1.47	20	200	13.13	0.29	7,725
Ragi	1.25	1.98	1584	0.26	21	150	9.47	0.04	1,675
Other millets	0.46	0.46	1001	0.10	21	150	14.99	0.01	502
Wheat	32.80	117.95	3595	27.88	85	530	14.74	14.78	358,371
Barley	0.61	1.92	3159	0.15	25	150	4.75	0.02	451
Total	109.83	332.05		81.45				45.78	1,068,031

implemented in over 14.10 million hectares, about 51% of the total pulse area of 27.72 million hectares, resulted in an estimated additional 3.76 million tonnes of pulse production with an estimated economic returns of ₹ 269,783 million (Table 2). The pulses are highly responsive to effective weed management, with relative yield gains often exceeding those reported for cereals Mishra and Choudhary (2026) reported 20–45% gain in pulse productivity due to adoption of IWM technologies. Greengram and chickpea contributed to the estimated increased production with each adding about 1.15 million tons due to their relatively higher area coverage under weed management (3.83 and 4.56 million hectares, respectively), coupled with substantial yield improvements. Blackgram and greengram had the highest relative yield responses of 42.25% and 41.72% increases over national average yields, corresponding to per-hectare gains of about 300 kg. Such strong responses reflect the high sensitivity of short-duration pulses to early-season weed competition (Choudhary *et al.* 2025b).

Pigeonpea has a longer growth duration; its wide row spacing and slow early growth make it vulnerable to weed pressure, particularly during the rainy season, thereby explaining the sizeable benefits from weed management (Kaur *et al.* 2015). Pigeonpea also exhibited a pronounced yield response (29.90%), contributing 0.65 million tons of additional production. In contrast, lentil showed limited absolute gains despite relatively higher baseline productivity, primarily due to very low weed management coverage (\approx 10% of area). This indicates a significant unrealized potential, as previous studies have reported yield losses of 25–50% in lentil under weedy conditions (Yadav *et al.* 2013). Overall, the findings underscore weed management as a high-impact intervention for enhancing pulse productivity, profitability, and national pulse availability. Expanding weed management coverage, particularly in area-dominant and short-duration pulses, could substantially bridge existing

yield gaps and support nutritional security and sustainable intensification in rainfed and semi-arid regions (Choudhary *et al.* 2025c).

Oilseeds

Weed management interventions across major oilseed crops covered 18.47 million hectares, accounting for about 61% of the total oilseed area of 30.44 million hectares, and resulted in an additional 5.36 million tonnes of oilseed production with an estimated economic return of ₹ 295,112 million (Table 3). These gains are substantial in view of the high yield losses (20–50%) commonly attributed to weed competition in oilseed crops, particularly during early growth stages (Choudhary *et al.* 2022). The results confirm that oilseeds are highly responsive to effective weed management, especially in crops with large spatial coverage. Soybean and groundnut emerged as the principal contributors to production and economic gains due to their extensive cultivated area and relatively high adoption of weed management practices. Soybean alone contributed 3.42 million tonnes of additional production, reflecting high coverage under weed management (88%) and a yield increase of 25.45% over the national average, which translated into the highest economic returns (₹ 167,274 million). Soybean is known to be particularly vulnerable to early-season weed competition because of its slow initial growth and wide row spacing, and yield losses of 30–40% under weedy conditions have been widely reported (Jadhav *et al.* 2025). Similarly, groundnut recorded an additional 1.30 million tonnes of production with 75% area coverage and a yield increase of 14.47%, consistent with earlier findings that timely weed control can enhance pod yield by 15–35% (Mehriya *et al.* 2021).

Among minor oilseeds, niger, linseed, and safflower exhibited the highest relative yield responses (20–38%). Although their absolute production gains were small due to limited area, the

Table 2. Weed management coverage and its impact on productivity and economic returns across major pulse crops in India (2024-25)

Crop	Area (mha)	Production (mt)	Productivity (kg/ha)	Estimated area under weed management (mha)	Estimated % of area coverage under weed management	Estimated crop productivity gain (kg/ha) due to IWM	Estimated % increase in yield over national average	Estimated additional crop production due to IWM (mt)	Estimated additional gains in economic return (Rs in million)
Pigeonpea	4.34	3.62	836	2.60	60	250	29.90	0.65	49,105
Blackgram	3.16	2.24	710	2.05	65	300	42.25	0.62	45,556
Greengram	5.90	4.24	719	3.83	65	300	41.72	1.15	99,869
Lentil	1.70	1.65	973	0.17	10	150	15.42	0.03	1,707
Chickpea	9.12	11.11	1218	4.56	50	250	20.53	1.14	64,424
Other pulses	3.51	2.80	799	0.88	25	200	25.03	0.18	9,121
Total	27.72	25.68		14.10				3.76	269,783

Table 3. Weed management coverage and its impact on productivity and economic returns across major oilseed crops in India (2024-25)

Crop	Area (mha)	Production (mt)	Productivity (kg/ha)	Estimated area under weed management (mha)	Estimated % of area coverage under weed management	Estimated crop productivity gain (kg/ha) due to IWM	Estimated % increase in yield over national average	Estimated additional crop production due to IWM (mt)	Estimated additional gains in economic return (Rs in million)
Groundnut	5.76	11.94	2073	4.32	75	300	14.47	1.30	87,938
Castor	0.97	1.79	1852	0.14	15	200	10.80	0.03	1,303
Sesame	1.58	0.89	567	0.32	20	150	26.46	0.05	4,381
Niger	0.10	0.04	394	0.01	10	150	38.07	0.00	132
Soybean	12.95	15.27	1179	11.40	88	300	25.45	3.42	167,274
Sunflower	0.19	0.24	1214	0.07	35	250	20.59	0.02	1,236
Rapeseed & mustard	8.66	12.67	1463	2.16	25	250	17.09	0.54	32,193
Linseed	0.17	0.11	666	0.03	20	250	37.54	0.01	465
Safflower	0.06	0.04	672	0.01	20	250	37.20	0.00	190
Total	30.44	42.99		18.47				5.36	295,112

Table 4. Weed management coverage and its impact on productivity and economic returns across major commercial crops in India (2024-25)

Crop	Area (mha)	Production (mt)	Productivity (kg/ha)	Estimated area under weed management (mha)	Estimated % of area coverage under weed management	Estimated crop productivity gain (kg/ha) due to IWM	Estimated % increase in yield over national average	Estimated additional crop production due to IWM (mt)	Estimated additional gains in economic return (Rs in million)
Sugarcane	5.45	454.61	83416	3.00	55	12000	14.39	35.97	122,298
Cotton	11.48	29.72	440	7.46	65	125	28.41	0.93	66,444
Potato	2.14	60.14	28103	0.86	40	5620	20.00	4.81	72,161
Total	19.07	544.48		11.32				41.71	260,903

strong percentage response indicates severe yield suppression under unmanaged weed conditions and highlights significant untapped potential if weed management is scaled up. In contrast, relatively lower gains in castor and rapeseed–mustard were mainly associated with limited area coverage under weed management, despite moderate yield improvements, suggesting that expansion of coverage rather than yield response *per se* is the primary constraint. Overall, the findings emphasize that scaling integrated, crop-specific weed management strategies in oilseeds can substantially narrow yield gaps, enhance domestic oilseed availability, and reduce import dependence, while improving farm profitability across both major and minor oilseed systems.

Commercial crops

Earlier studies have reported yield reductions of 20–60% in commercial crops under unmanaged weed conditions, particularly during early crop establishment (Chauhan and Mahajan 2014). Weed management interventions in sugarcane, cotton, and potato estimated covered 11.32 million hectares, representing nearly 59% of the total cropped area of 19.07 million hectares under these crops, and resulted in an estimated additional 41.71 million tonnes of production with an estimated economic return of ₹

260,903 million (Table 4). The magnitude of these gains highlights the critical role of weed management in high-value commercial crops, where yield losses due to weeds are often severe and economic stakes are high. Sugarcane is highly susceptible to weed competition during the first 90–120 days after planting, when weeds compete aggressively for nutrients, moisture, and light, leading to long-term yield penalties if not controlled (Suganthi *et al.* 2019). Sugarcane accounted for the largest share of gains, primarily due to its very high biomass productivity and substantial per-hectare yield response (12,000 kg/ha). Effective weed control resulted in an additional 35.97 million tonnes of cane production and ₹ 122,298 million in economic returns. The results reaffirm that timely weed management during the formative growth phase is essential for realizing the yield potential of sugarcane.

Potato is a short-duration, nutrient- and water-intensive crop, and early weed interference has been shown to reduce tuber initiation and bulking, resulting in yield losses of 30–40% (Jabran *et al.* 2023). Potato also showed a strong response to weed management, recording a 20% yield increase and an additional 4.81 million tonnes of production despite moderate area coverage (40%). The observed gains are consistent with earlier findings emphasizing the importance of maintaining weed-free conditions during the first 30–

45 days after planting. Cotton's long vegetative phase and slow early growth make it particularly vulnerable to weed competition, and IWM has been shown to significantly improve yield and resource-use efficiency (Manalil *et al.* 2017). Cotton contributed relatively lower absolute production gains (0.93 million tonnes) but exhibited a high relative yield increase (28.41%) due to effective weed control across 65% of its cultivated area, generating substantial economic benefits (₹ 66,444 million). Overall, the results demonstrate that expanding timely and IWM in commercial crops can deliver disproportionate productivity and profitability gains, reinforcing its role as a core component of sustainable intensification strategies.

Overall weed management coverage and its impact

At the national level, weed management interventions covered an estimated 125.33 million hectares, representing about 67.0% of the total cropped area across major crop groups (187.06 million hectares), and resulted in an estimated additional 96.62 million tonnes of agricultural production with an estimated economic return of ₹ 1,893,828 million (Table 5). These aggregated gains highlight the pervasive impact of weeds as a biotic constraint and the substantial production penalties associated with inadequate control, which are often estimated at 25–40% across crops in tropical agriculture (Chauhan *et al.* 2012).

Constraints and opportunities for scaling up IWM adoption

Based on the interactions with different stakeholders during collection of the data used for the estimated in the study, a few constraints and opportunities for scaling up of IWM adoption were identified. They include:

Constraints for scaling up IWM adoption

a. Knowledge and skill gaps: Limited knowledge on weed ecology, critical period of crop–weed competition, and lack of awareness on possible

integration of cultural, mechanical, and chemical methods amongst farmers is restricting the effective IWM adoption by farmers.

b. Labour and mechanization constraints: High labour requirements for manual/mechanical weeding and limited access to suitable improved agricultural implements (*e.g.*, mechanical weeders, inter-row cultivators), especially during labour scarcity.

c. Short-term cost and risk perception: IWM often involves higher initial costs and delayed benefits compared to sole herbicide use and thus discouraging IWM adoption by smallholders with limited risk-bearing capacity.

d. Herbicide-centric practices: Over-reliance on herbicides usage to manage weeds, driven by ease of use and aggressive marketing by industry, has reduced farmer's interest in diversified weed management strategies.

e. Policy and institutional limitations: Inadequate extension support, weak custom-hiring infrastructure, and limited incentives for non-chemical approaches constrain large-scale dissemination of improved IWM technology and its adoption.

Opportunities for scaling up IWM adoption

a. Rising herbicide resistance and weed shifts: Increasing cases of herbicide resistance and hard-to-control weeds create a strong rationale for promoting IWM as a sustainable alternative.

b. Advances in mechanization and precision agriculture: Availability of weeders, residue managers, drone-based herbicide applicators, and site-specific weed management tools enhances operational efficiency of IWM.

c. Conservation agriculture and climate-smart systems: Expansion of zero-till, residue retention, and diversified cropping systems aligns well with ecological IWM principles.

Table 5. Weed management coverage and its impact on productivity and economic returns across major crop group in India (2024-25)

Crop	Area (mha)	Production (mt)	Estimated area under weed management (mha)	Estimated % of area coverage under weed management	Estimated additional crop production due to IWM (mt)	Estimated additional gains in economic return (Rs in million)
Cereals	109.83	332.05	81.45	74.16	45.78	1,068,031
Pulses	27.72	25.68	14.10	50.85	3.76	269,783
Oilseeds	30.44	42.99	18.47	60.67	5.36	295,112
Commercial crops	19.07	544.48	11.32	59.34	41.71	260,903
Total	187.06	945.19	125.33	67.00	96.62	1,893,828

d. Economic and environmental co-benefits: IWM reduces long-term weed pressure, input costs, and environmental risks while improving yield stability and profitability.

e. Policy support for sustainable intensification: National initiatives on resource-use efficiency, natural farming, and sustainable agriculture provide a conducive policy environment for IWM mainstreaming.

Way forward

It was estimated that 61.73 million hectares which are still left unmanaged in the country under different field crops and scaling up weed management across this area could generate an additional 55.34 million tonnes of agricultural output and a substantial economic gain of Rs 932,201 million (Table 6). Presently, farmers are unable to utilize

available weed management technologies due to various constraints, listed above. Hence, in years to come, it is essential to take the technology to the farmers and encourage them to adopt by creating awareness amongst farmers of improved weed management technologies by capacity building and training, *etc.* The adoption of improved weed management practices by the majority of the farmers would enhance crop productivity and farm income, without expanding cultivated area and strengthen the national food security.

Two future targets to achieve the Viksit Bharat Goal @ 2047, with respect to weed management, include:

1. To create awareness on the importance of IWM adoption amongst farmers and bring entire cropped area under IWM adoption

Table 6. Potential crop productivity and economic gains of major field crops in India due to projected feasible acreage expansion with improved weed management technologies adoption

Crops	Projected extended area to be covered with improved weed management (mha)	% of total cultivable area	Estimated productivity gain (kg/ha)	Estimated additional crop production (mt) due to IWM adoption	Estimated additional economic gain (Rs in millions) due to adoption of improved weed management technologies
<i>Cereals</i>					
Rice	11.28	22	500	5.64	129,706
Maize	1.69	14	1000	1.69	37,663
Jowar	2.80	70	200	0.56	18,854
Bajra	5.89	80	200	1.18	30,899
Ragi	0.99	79	150	0.15	6,300
Other minor millets	0.36	79	150	0.05	1,887
Wheat	4.92	15	530	2.61	63,242
Barley	0.46	75	150	0.07	1,659
Total	28.38			11.95	290,210
<i>Pulses</i>					
Pigeonpea	1.73	40	250	0.43	32,737
Blackgram	1.10	35	300	0.33	24,530
Greengram	2.06	35	300	0.62	53,776
Lentil	1.53	90	150	0.23	15,367
Chickpea	4.56	50	250	1.14	64,424
Other pulses	2.63	75	200	0.53	27,362
Total	13.63			3.28	218,197
<i>Oilseeds</i>					
Groundnut	1.44	25	300	0.43	29,313
Castor	0.82	85	200	0.16	7,382
Sesame	1.26	80	150	0.19	17,526
Niger	0.09	90	150	0.01	1,189
Soybean	1.55	12	300	0.47	22,810
Sunflower	0.13	65	250	0.03	2,295
Rapeseed & mustard	6.49	75	250	1.62	96,580
Linseed	0.14	80	250	0.03	1,859
Safflower	0.05	80	250	0.01	760
Total	11.97			2.97	179,713
<i>Commercial crops</i>					
Sugarcane	2.45	45	12000	29.43	100,062
Cotton	4.02	35	125	0.50	35,778
Potato	1.28	60	5620	7.22	108,241
Total	7.76			37.15	244,081
Grand total	61.73	33		55.34	932,201

- To introduce a certain degree of weed management adoption in the presently unweeded cropped area of different crops by demonstrating the potential productivity and economic gains with the adoption of improved weed management

The future target achievement would lead to an estimated potential additional 55.34 million tonnes production of cereals; 11.95 million tonnes of millets; 3.28 million tonnes of pulses; 2.96 million tonnes of oilseeds and 37.15 million tonnes of commercial crops with total additional economic gain of Rs 932,201 million (Table 6).

Conclusions

At the national scale, the scaling up of integrated weed management across varying crops has the potential to generate additional economic gains of nearly ₹ 0.93 trillion and thus indicating that weed management is a core pillar of sustainable agricultural intensification in India. Overall, the findings of this study conclusively establish weed management as a high-impact, high-return intervention for bridging crop yield gaps and enhancing national agricultural output. Across food grains, pulses, oilseeds, and commercial crops, the timely and integrated weed management consistently improves crop productivity and farm profitability. Expanding weed management coverage particularly through crop- and system-specific integrated approaches in different agro-ecological zones can substantially improve food and nutritional security, reduce import dependence in oilseeds, and strengthen farm incomes.

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RESEARCH ARTICLE

Predicting the potential distribution of *Echinochloa colona* (L.) Link. and *Cyperus rotundus* L. under future climatic scenarios in India

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ABSTRACT

Weed's geographical and temporal expansion severely affects the global biodiversity, agricultural ecosystems and economy of the country like India. Therefore, in order to help and better prioritize the management tactics, MaxEnt model was used to predict the current and future distribution of *Echinochloa colona* and *Cyperus rotundus*, two economically important weeds of agricultural ecosystems. With the help of 552 and 343 occurrence points of *E. colona* and *C. rotundus*, respectively, along with 8 bioclimatic parameters, elevation, and soil layers; modelling was performed and predictions were made for probable hotspots of the species in future changing climate scenario. The area under the receiver operating characteristics (ROC) curve (AUC) was used to test the model's accuracy, and Jackknife test was used to observe the variable importance for both the species. The model predicts that under Representative Concentration Pathway (RCP) 4.5 for both 2050 and 2070, climatic conditions were generally highly suitable for *E. colona*, except for certain areas in southern, western, and northern India. Whereas, under RCP 8.5 for the same years, a notable reduction in suitable areas is predicted for the species, particularly in Central India. On the other hand, *C. rotundus* is projected to contract the suitable areas in future climates under both the scenarios depicting the reduced suitability under future climate. Findings of this study would contribute to a better understanding of the nature of the niche shift of both the species and the potential for invasion under future climate scenarios. This will help in understanding the impact of the species and in making informed decisions on matters related to biodiversity, public health, agriculture, and the economy.

Keywords: *Cyperus rotundus*, Climate change, *Echinochloa colona*, MaxEnt model, Potential distribution, Weed species distribution modelling

INTRODUCTION

Biotic and abiotic factors contribute in crop yield and economic losses. Among the major biotic constraints, weeds are the significant pest affecting agricultural production, agrobiodiversity and natural water bodies (Gharde *et al.* 2018). They can negatively impact the crop by competing for resources such as water, sunlight and space; sheltering crop pests; interfering with water management; reducing the yield and quality and subsequently increasing the cost of the production (Chauhan 2020, Rao 2022). The alien invasive weeds (AIW) are those, which are introduced into places outside their natural range, adversely affecting native biodiversity, ecosystem or human well-being. These species are introduced intentionally or accidentally outside their natural habitat, where they exhibit the

ability to establish themselves, invade, out-compete native weeds and take over the new environment within short span of time. One of the major disadvantages of their introduction is extinction of native species, which has been well documented (Blackburn 2019). For instance, a tree species Saint Helena olive (*Nesiota elliptica*) endemic to Saint Helena that became extinct due to habitat destruction and competition with invasive alien plants introduced to the island during human settlement and agriculture (Cronk 2016). Further, uncontrolled expansion of weeds in agriculture ecosystem may cause huge crop yield losses (Rai and Singh 2020).

Climate change, mostly known by the term “Global Warming”, is now a well-accepted phenomenon which may be due to both natural and human intervention. According to Inter-governmental Panel on Climate Change (IPCC), “Climate change refers to any change in the state of climate identified by fluctuations in the mean and/or the variability of its properties due to natural event or human activities, and that persists for a longer period like decades or

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more” (IPCC 2007, Anwar *et al.* 2021). Recent IPCC report states that the Earth has already warmed about 1.1–1.2 °C since pre-industrial times, will likely reach 1.5 °C between 2030–2040, and could warm up to ~5 °C by 2100 under high emissions (IPCC 2023). Climate change is also expected to affect the distribution and occurrence of the weeds in future (Gharde *et al.* 2024). It will have a profound effect on crop protection, including the effects on pests, diseases and weeds (IPCC 2022). Furthermore, the physiology and biological cycle of the weeds and their competitive relationship with crops will also be affected significantly (Ziska and Dukes 2011). Climate change may also affect the geographic distribution of a native species or invasion of crops by a new weed species (López-Tirado and Gonzalez-Andújar 2023). To minimize the effect of weed success favoured by climate change, there is need to predict the potential geographical distribution of species accurately. This will help in understanding the impact of the species and in making informed decisions on the matter related to biodiversity, public health, agriculture and the economy. Apart from this, it will also help in early detection of the hot spots of the species enabling prompt actions in order to reduce management cost after its introduction in new places (Dorji *et al.* 2022, Singh *et al.* 2024).

Predictive models used for the species distribution modelling are powerful tools that can assist in making the decision on the management of these invasive species under different climate scenarios. Some commonly used models are CLIMEX, BIOCLIM, MaxEnt and CLIMATCH known for their simplicity and the data accessibility (Srivastava *et al.* 2019, Gharde *et al.* 2023a). This modelling approach is a well-established approach to model and project the habitat suitability of a species based on their current distribution relative to climatic factors (Elith *et al.* 2006, Gharde *et al.* 2023b). This technique has gained importance in ecology, biogeography, biodiversity conservation and management of natural resources (Adhikari *et al.* 2019). Numerous studies have been conducted in the past to assess the impact of climate change on the potential distribution of the species and found the difference in the results (Merow *et al.* 2017). In India, widespread obnoxious invasive alien weeds such as *Parthenium hysterophorus*, *Lantana camara*, *Chromolaena odorata* (Patil and Janarthanam 2013), *Cassia tora* (Panda *et al.* 2018), *Tridax procumbens* (Panda and Behera 2019), *Ethulia gracilis* (Aravind *et al.* 2022), *Calyptocarpus vialis* (Lal *et al.* 2024), *Phalaris minor* (Gharde *et al.* 2023a) *etc.* have been studied for their probable geographical distribution in future climatic scenarios.

Holm (1969) listed 10 serious weed species that cause serious consequences to agriculture worldwide which also includes purple nutsedge (*Cyperus rotundus* (L.) and jungle rice (*Echinochloa colona* (L.) Link.). These species are capable of adapting different environmental conditions, and have spread all over the world (Holm 1969). *Echinochloa colona* ranked as the world’s fourth worst weeds infesting numerous crops in several countries and causing significant reduction in the yield of crops (Holm *et al.* 1991). However, it tends to occur mostly in rainfed agriculture system. Due to its characteristics such as plasticity in morphology, phenology, fast growth, prolific seed production, seed dormancy, and adaptability to a wide range of environments, it contribute to the successful establishment of this species in agroecosystems (Rao 2021). Purple nutsedge (*Cyperus rotundus* L.), native to India, is considered as economically damaging weed, which has been widely adapted in the countries across Africa, America, South Asia, and southern/central Europe, significantly impacting the tropical and subtropical regions of the globe (Srivastava *et al.* 2013). This weed cause huge yield losses (20–90%) in various crops across the world (Peerzada 2017). Due to its distinctive characteristics such as high rate of reproduction, perennial nature, genetic diversity, ability to adapt to adverse environments, easy dispersion and strong competitive abilities help this weed to occur in a wide range of agro-climatic regions (Peerzada 2017). As a glabrous perennial sedge, it can grow under various soil conditions, preferably in moist soils, and is commonly found in wasteland, gardens, orchards, and cultivated areas (Khalid and Siddiqui 2014). In particular, it can be a threat to croplands, resulting in the loss of food and feed valuable to human beings (Holm 1969).

Keeping in view, the harmful effects caused by these two weeds in agriculture ecosystem, it is necessary to explore the expansion risk of these weeds in India. Therefore, the aim of this study was to model and project the habitat suitability of two important weed species of agricultural system, *viz.* *E. colona* and *C. rotundus* under current as well as future climatic scenarios.

MATERIALS AND METHODS

Collection of occurrence data of the species

Occurrence data of the two species, *viz.* *E. colona* and *C. rotundus* was obtained from the sources such as Flora of Peninsular India, Herbarium JCB, Centre for Ecological Sciences, Indian Institute of Science, Bangalore (<http://flora-peninsula-indica.ces.iisc.ac.in/>); Centre for Agriculture and

Biosciences International (CABI); Global Biodiversity Information Facility (GBIF) (<https://doi.org/10.15468/dl.ja9yr2> and <https://doi.org/10.15468/dl.m35m8j>); iNaturalist; India Biodiversity Portal; and other published literature (**Table 1**). *E. colona* is native to tropical and subtropical Asia and is now widespread in the warm regions of Asia, Africa, and Australia (Holm *et al.* 1991, Lazarides 1980, Peerzada *et al.* 2016), therefore, occurrence data for both native and invaded range (India) was collected for this species. For *C. rotundus*, occurrence records collected from India were used for modelling, as India represents its native range. For those published literature where geo-coordinates of the study location was not provided, they were collected from google search engine to locate the site of the experiment. After the elimination of ambiguous and duplicate records, 552 and 343 occurrence points were retained for further analysis for *E. colona* and *C. rotundus*, respectively (**Figure 1**).

Climate data

Climatic data for 19 bioclimatic variables (bio1 to bio19; **Table 2**) with a spatial resolution of 30 arc-seconds (~1 km²) were downloaded from the WorldClim database (www.worldclim.org). Elevation data from the Shuttle Radar Topography Mission (SRTM) were also obtained from the same source. All the downloaded layers were converted into ASCII (American Standard Code for Information Interchange) format using QGIS version 3.36. Future climate data for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 for the years 2050 and 2070, at the same 30 arc-seconds resolution, were downloaded in ASCII format from the Climate Change, Agriculture and Food Security (CCAFS) website (www.ccafs-climate.org) (Gharde *et al.* 2023a). According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC,

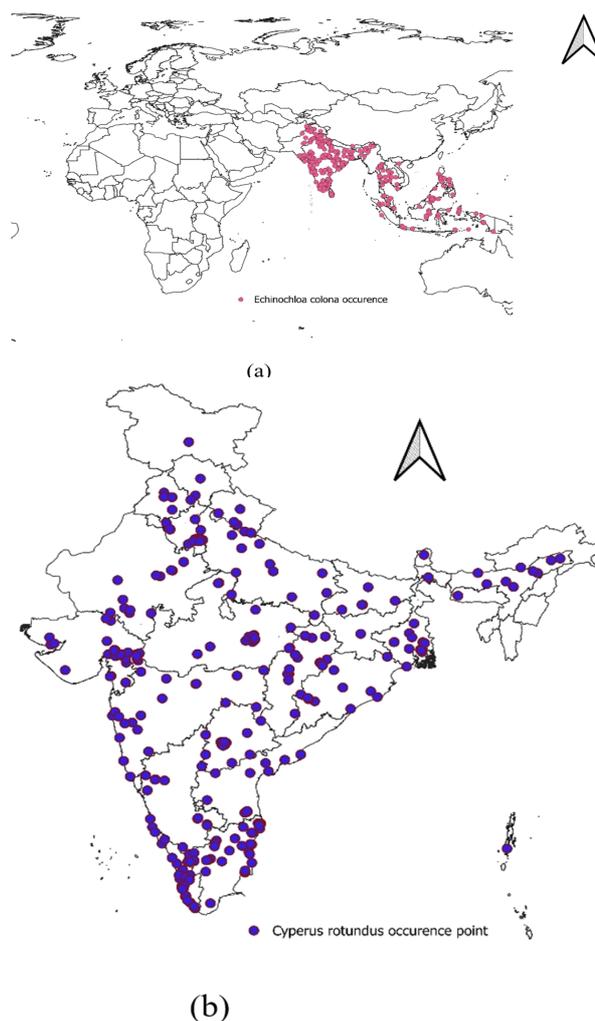


Figure 1. Maps depicting the occurrence points of (a) *Echinochloa colona* and (b) *Cyperus rotundus* in the study region

2014), four RCPs were described. Among them, RCP 4.5 represents a moderate greenhouse gas emission scenario (with a projected temperature rise of about 2-3°C), while RCP 8.5 represents a high emission scenario (with a projected temperature rise of around

Table 1. List of published literature from where occurrence records were collected for *Echinochloa colona* and *Cyperus rotundus*

Species	Source of data
<i>Echinochloa colona</i>	Das <i>et al.</i> (1996), Rao and Rao (2006), Swain <i>et al.</i> (2008, 2012), Babu (2012), Maharaj and Prabhakaran (2014), Borkar <i>et al.</i> (2015), Kumar <i>et al.</i> (2016), Chopra <i>et al.</i> (2017), Praneetha <i>et al.</i> (2017), Aparna <i>et al.</i> (2018), Krishnaveni and Prasanna (2019), Borkar <i>et al.</i> (2021), Dhankar <i>et al.</i> (2022), Kaushal <i>et al.</i> (2023) GBIF (https://doi.org/10.15468/dl.p6sbf4 ; https://doi.org/10.15468/dl.zupkex ; https://doi.org/10.15468/dl.jbjdix ; https://doi.org/10.15468/dl.uc9d6k ; https://doi.org/10.15468/dl.kqdtgv ; https://doi.org/10.15468/dl.tummy99 ; https://doi.org/10.15468/dl.s49hma ; https://doi.org/10.15468/dl.c4wuz6 ; https://doi.org/10.15468/dl.k5ncnb ; https://doi.org/10.15468/dl.bgdwxa ; https://doi.org/10.15468/dl.cpwyzq ; https://doi.org/10.15468/dl.gk2tm7 ; https://doi.org/10.15468/dl.d28bzy)
<i>Cyperus rotundus</i>	Satao <i>et al.</i> (1995), Babu and Kandasamy (1997), Gupta <i>et al.</i> (2002), Chopra and Chopra (2004), Ghorai <i>et al.</i> (2005), Kumar and Mishra (2005), Sharma and Gupta (2007), Pal (2009), Singh <i>et al.</i> (2010), Venkatasubramanian <i>et al.</i> (2010), Kumar <i>et al.</i> (2012), Samariya and Sarin (2013), Kumar <i>et al.</i> (2013), Singh <i>et al.</i> (2014), Nidugala <i>et al.</i> (2016), Desai <i>et al.</i> (2017), Dhyani (2017), Edwina and Leela (2020), Golla <i>et al.</i> (2022), Vadivel <i>et al.</i> (2022)

Table 2. List of climatic variables

Code	Variable name
bio1	Annual mean temperature
bio2	Mean diurnal range [mean of monthly (max temp - min temp)]
bio3	Isothermality (bio2/bio7) (* 100)
bio4	Temperature seasonality (standard deviation *100)
bio5	Max temperature of warmest month
bio6	Min temperature of coldest month
bio7	Temperature annual range (bio5- bio6)
bio8	Mean temperature of wettest quarter
bio9	Mean temperature of driest quarter
bio10	Mean temperature of warmest quarter
bio11	Mean temperature of coldest quarter
bio12	Annual precipitation
bio13	Precipitation of wettest month
bio14	Precipitation of driest month
bio15	Precipitation seasonality (coefficient of variation)
bio16	Precipitation of wettest quarter
bio17	Precipitation of driest quarter
bio18	Precipitation of warmest quarter
bio19	Precipitation of coldest quarter

5°C). The future climate data used in this study were generated from the Canadian Earth System Model (CanESM2) developed by the Canadian Centre for Climate Modelling and Analysis. These datasets were statistically downscaled from a Global Circulation Model (GCM) using WorldClim version 1.4.

Data preprocessing and modelling approach

Before the modelling, data were pre-processed to make them ready for further analysis. Occurrence points for the species were prepared in csv file format with species name along with latitude and longitude data. For 19 bioclimatic variables downloaded from WorldClim database, correlation analysis was done and variables having Pearson correlation coefficient values $|r| \geq 0.8$ were excluded from the analysis to avoid multicollinearity effects from the data. After following this criterion, eight bioclimatic variables along with elevation (and soil in case of *C. rotundus*) were chosen for further analysis.

In case of *E. colona*, raster layers of environmental variables were kept for whole world, however, they were clipped to match the extent of the study region for *C. rotundus*. All the raster layers of environmental variables were converted to follow the uniform projection system (EPSG: 4326 WGS-84) and 30 arc seconds spatial resolution. The MaxEnt v3.4.4 software (downloaded from https://biodiversityinformatics.amnh.org/open_source/maxent/) was used to model the present and future distribution of both the species using occurrence data and environmental variables. The relative importance of the variables was established using the jackknife method (Liao *et al.* 2017). Before the model run, the output file format for the model was set to ‘cloglog’.

A ten-fold cross-validation approach was used to minimize the uncertainties in the response curves and prediction on occurrences. The final model output was thus obtained through averaging these layers. This technique randomly split the occurrence data into 10 number of equal-size “folds” and models are formed using nine folds leaving each fold in turn and then left-out folds are then used for model validation. Thus, this technique use all data for validation purpose. The algorithm in MaxEnt was set to ‘auto features’ and the procedure was set to run 500 iterations with 10,000 background points with a regularization multiplier of 1. The Area under the receiver operating characteristics (ROC) curve (AUC) was used to test the model’s accuracy. AUC values greater than 0.7 are generally considered to indicate good model performance, whereas values exceeding 0.9 are regarded as outstanding. AUC value less than 0.7 is considered as ‘fair’. All environmental layers were converted into ASCII format before running the model (Thapa *et al.* 2018, Singh *et al.* 2024). MaxEnt provides gradient surface for the suitability of areas with values between 0-1 based on suitability.

RESULTS AND DISCUSSION

Model performance

The mean omission and predicted area for the *E. colona* and *C. rotundus* are shown in **Figure 2**, which shows that the models performed better than the random one (AUC 0.5) when evaluated for omission. The MaxEnt model can generate the area under ROC curve and find the models’ AUC value on its own, which can be utilized as model selection criteria. In this study, the average AUC values are 0.958 and 0.735 for *E. colona* and *C. rotundus*, respectively. This indicated that models performed much better than the random prediction (AUC 0.5) and suggesting that the outcomes of the prediction were more precise. AUC value suggested that in case of *E. colona*, the model-predicted distribution completely matched the species’ actual distribution.

Importance of bioclimatic variables

In order to determine the importance of the bioclimatic variables in prediction, jackknife test was used available in MaxEnt. The MaxEnt generates the result of jackknife test for regularized training gain, test gain and AUC for both the species.

Jackknife test revealed that two bioclimatic variables Annual Mean Temperature and Mean Temperature of Warmest Quarter provided higher test gain in case of *E. colona*, however, Min Temperature

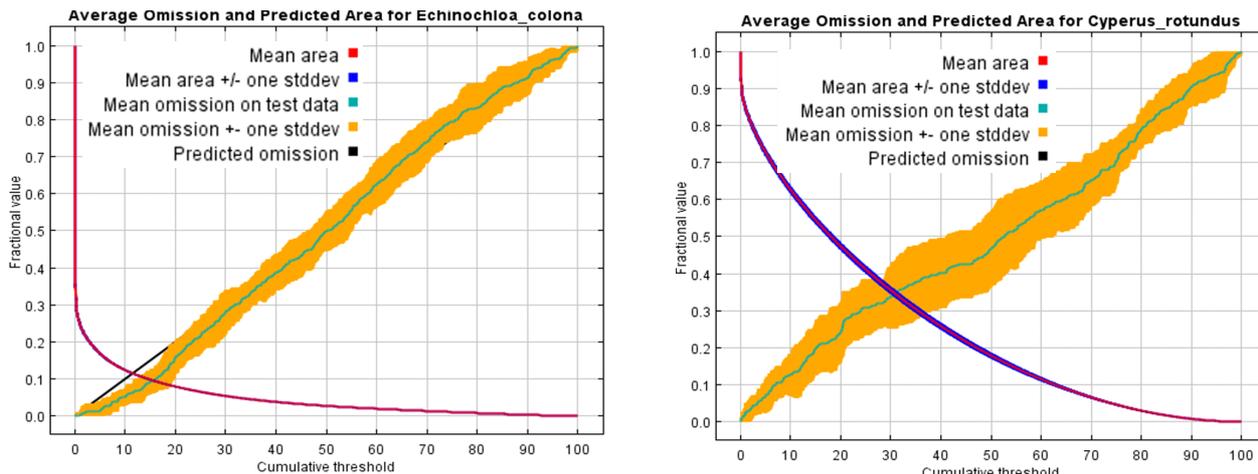


Figure 2. Plot showing the average omission rate and predicted area for *Echinochloa colona* and *Cyperus rotundus* as a result of the cumulative threshold being approximately over 10 duplicate runs

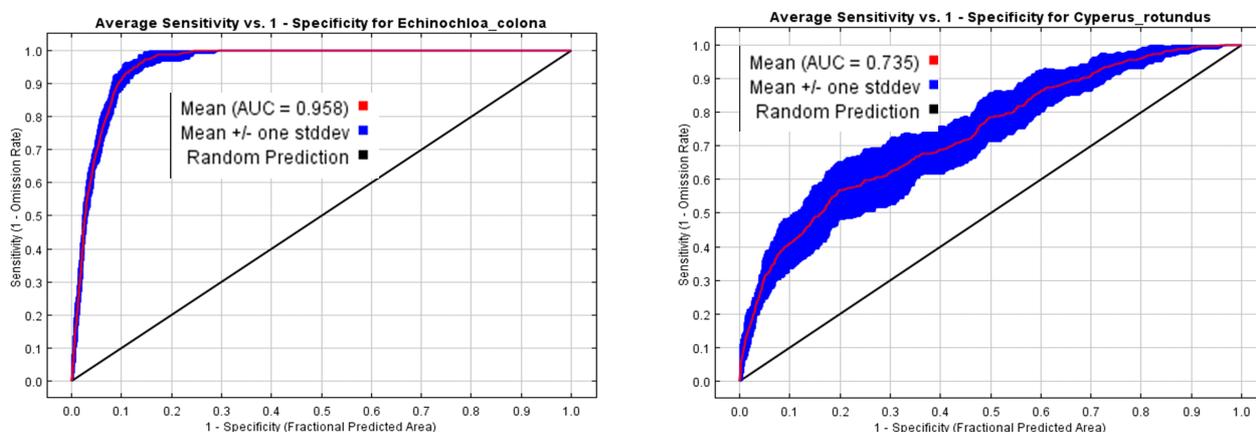
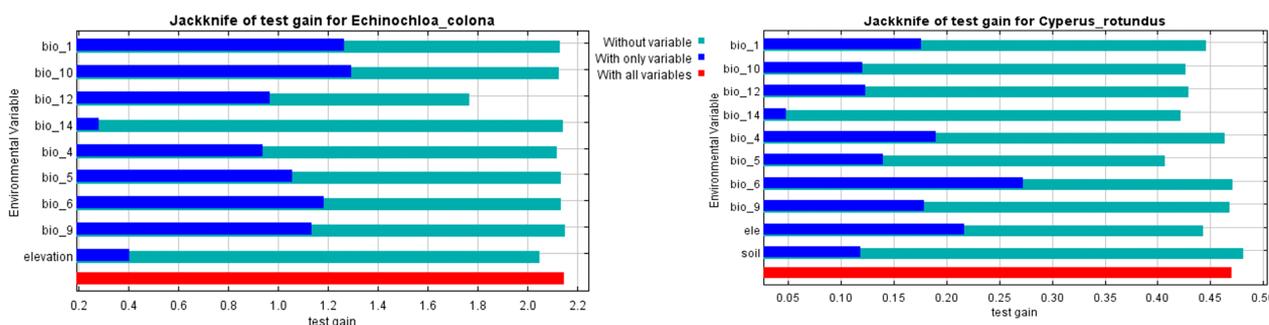


Figure 3. Plot showing the AUC values for *Echinochloa colona* and *Cyperus rotundus* as a result of the 10-fold cross-validation method



Note: bio_1 = Annual Mean Temperature; bio_4 = Temperature Seasonality; bio_5 = Max Temperature of Warmest Month; bio_6 = Min Temperature of Coldest Month; bio_9 = Mean Temperature of Driest Quarter; bio_10 = Mean Temperature of Warmest Quarter; bio_12 = Annual Precipitation; bio_14 = Precipitation of Driest Month; Elevation, above mean sea level

Figure 4. Significance of bioclimatic variables for the distribution of *Echinochloa colona* and *Cyperus rotundus* as a result of jackknife test

of Coldest Month and elevation are found to be affecting the distribution of *C. rotundus* significantly. However, it was observed that for *E. colona*, Annual Precipitation caused the greatest decrease in test gain when omitted from the analysis. This indicates that it contains more unique information than the other bioclimatic variables and has the strongest influence on model performance in its absence. These findings revealed that these variables made significant

contribution in increasing the predictability in the modelling process. **Figure 5a** revealed that higher suitable conditions for *E. colona* are characterized by annual mean temperature at 23°C. Lin and Kuo (1996) also reported that non-dormant seeds of *E. colona* can germinate well when mean temperatures are 20–34°C. In the present study, test also revealed that Mean Temperature of Warmest Quarter at 32°C are ideal for the species and temperature beyond that

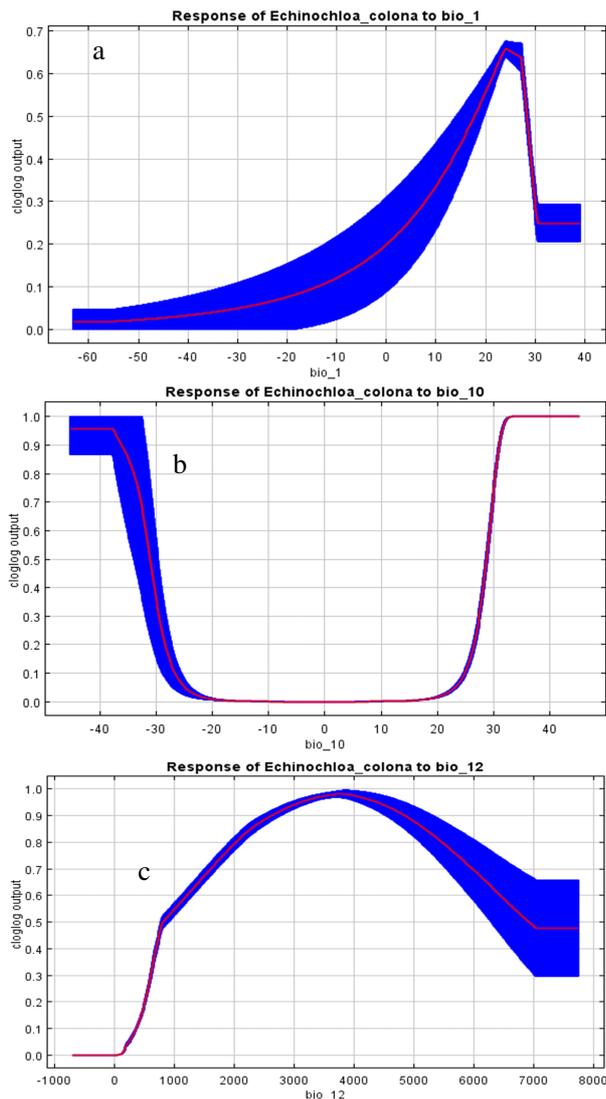


Figure 5. Response of the *Echinochloa colona* with respect to significant environmental variables

is giving the same favourability conditions for the species without any gain, however, it also shows that annual precipitation ranged between 3000-4000 mm are highly promising conditions for species development. This commemorates the findings of Civico and Moody (1979) where they found that *E. colona* is not affected by the flooding conditions to a depth of 5 cm, once established, and thus, can survive in both flooded and non-flooded rice fields. However, submerged conditions make it die. Further, it is observed that growth of *E. colona* was reduced when they were subjected to drought stress (Chun and Moody 1985). The plants produced shorter panicles and initiated later compared to those grown under well-watered conditions. These studies support that the species requires higher precipitation (not submerged) areas for the development. In case of *C. rotundus*, Minimum Temperature of Coldest Month >22°C is found to be suitable for the species which

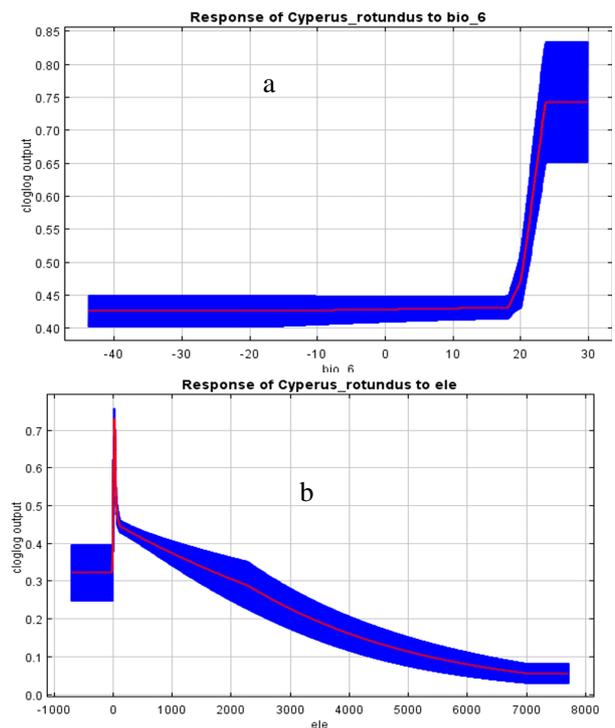


Figure 6. Response of the *Cyperus rotundus* with respect to significant environmental variables

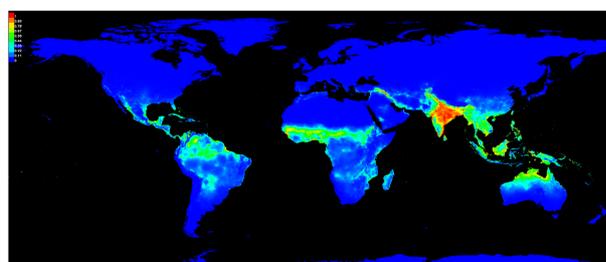
indicates its tendency to tolerate the high temperature (Figure 6), as also observed by Dor and Hershenhorn (2013). Santos *et al.* (1997) also reported that due to its rapid growth, perennial nature, and abundant tuber production, this weed is highly invasive and difficult to control in warmer regions. Our graph depicts that at lower temperature (<18°C) species favourability decreases. Elevation was also observed as significant factor affecting the distribution of the species. Analysis revealed that with increasing altitudes, species performance in a place is decreasing which revealed its non-adaptability to places with high altitudes limited by cold temperatures (Holm *et al.* 1977).

Distribution pattern of *Echinochloa colona* in current and future climatic scenarios

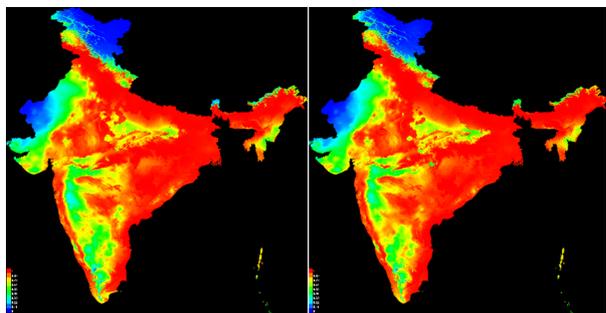
In current climatic conditions, central part of India including eastern states West Bengal and Odisha showing highly suitable areas for *E. colona*. Other parts of India including extreme north, west, north-east, Indo-Gangetic plains and southern India (excluding some parts of Kerala) are found to be moderately suitable for the species (Figure 7a). However, in future climatic scenarios most parts of the India are found to be highly suitable for the species (Figure 7b-e). Analysis revealed that under RCP 4.5 for both years 2050 and 2070 (Figure 7b and c), climatic conditions were found to be highly suitable for the species excluding some parts of the

south, west and northern India, however, a significant decrease in areas of suitability especially in Central India is predicted under RCP 8.5 for both the years (Figure 7d and e). Instead, climatic suitability is shifted to the coastal parts of India along with eastern, North-eastern and Northern states.

In case of *C. rotundus*, most of the parts of India (excluding western Himalaya region, parts of Rajasthan, few places of central plains and western and southern plateau and hills) were found to be moderately suitable (green colour) for *C. rotundus* (Figure 8a), however, a significant decrease in suitable areas were found under RCP 4.5 and 8.5 for both the years 2050 and 2070 due to increase in temperature. Very high and high suitable areas (red and yellow colour) found to be increased under RCP

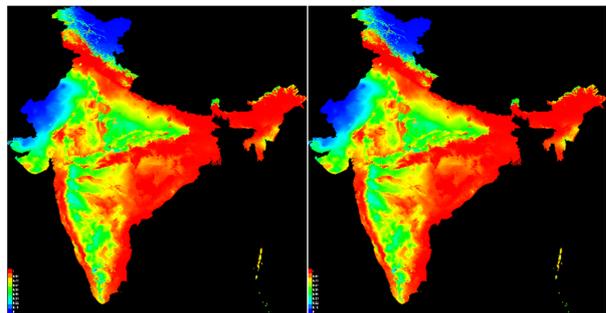


(a) Current distribution



(b) RCP 4.5 2050

(c) RCP 4.5 2070



(d) RCP 8.5 2050

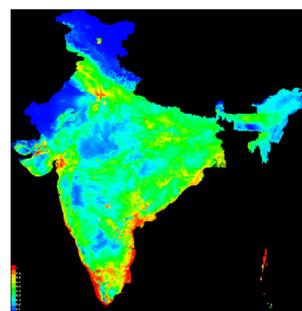
(e) RCP 8.5 2070

In maps, red colour depicts very high suitable, yellow colour as high suitable, green colour as moderately suitable and blue colour as not suitable areas

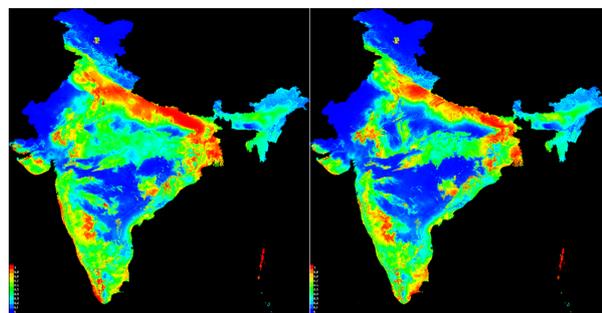
Figure 7. Predicted distribution maps of *Echinochloa colona* under (a) current climate; and future climatic scenarios (b) RCP 4.5 for 2050 (c) RCP 4.5 for 2070 (d) RCP 8.5 for 2050 and (e) RCP 8.5 for 2070

4.5 for both the years with slight decrease in 2070 as compared to 2050 (Figure 8b and c). Indo-Gangetic plains were found to be highly suitable (red colour) for the species including very few parts of the country. This species is expected to find very few areas of the country as suitable areas. The species suitability conditions were found in southern states including few areas in west, east and north-eastern states (Figure 8b and c). The suitability was further decreased in RCP 8.5 2050 and 2070 for the species where very few areas of southern and north-eastern states were found to be suitable (very high, high and moderate) for the species (Figure 8d and e).

Thus, by identifying climatically and environmentally suitable areas, early detection and

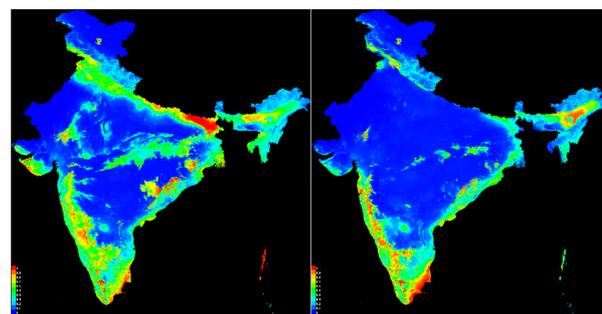


(a) Current distribution



(b) RCP 4.5 2050

(c) RCP 4.5 2070



(d) RCP 8.5 2050

(e) RCP 8.5 2070

In maps, red colour depicts very high suitable, yellow colour as high suitable, green colour as moderately suitable and blue colour as not suitable areas

Figure 8. Predicted distribution maps of *Cyperus rotundus* under (a) current climate; and future climatic scenarios (b) RCP 4.5 for 2050 (c) RCP 4.5 for 2070 (d) RCP 8.5 for 2050 and (e) RCP 8.5 for 2070

preventive management in regions are possible that are at high risk of invasion but not yet heavily infested. This supports a shift from reactive control measures to proactive planning. The models help prioritize surveillance efforts, optimize the allocation of limited resources such as labour, herbicides, and biological control agents, and reduce unnecessary expenditure in low-risk areas. Furthermore, the study identifies key environmental drivers influencing weed distribution, which aids in developing habitat-specific and climate-informed management strategies for both the species. This study also forecasts potential range expansion or contraction, allowing policymakers and land managers to design long-term adaptation and mitigation strategies. Overall, the study provides a scientific basis for risk assessment, policy formulation, and sustainable, cost-effective weed management planning.

Conclusion

In the present study the impact of global climate change on the distribution of *Echinochloa colona* and *Cyperus rotundus* was projected. Our findings revealed that *E. colona* is expected to expand its areas in the country in future climatic scenarios irrespective of the RCPs for both the years 2050 and 2070 while *C. rotundus* is showing overall contraction in the invaded areas than the current geographical distribution. However, through modelling highly favourable areas are projected to increase for *C. rotundus* in future climate. Thus, both the species studied are responding differently to future climate. The findings of this study will not only help to make informed decisions on the matter related to agriculture, biodiversity, public health and the economy but it will also help in early detection of the species to enable speedy actions to reduce their management cost.

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RESEARCH ARTICLE

Impact of integrated weed management strategies on weeds and rhizosphere microbial population in rice established by system rice intensification (SRI)

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ABSTRACT

A field experiment was conducted during the kharif seasons of 2022 and 2023 at the Experimental Farm, School of Agriculture, Bharath Institute of Higher Education and Research, Tamil Nadu, to assess the impact of integrated weed management treatments on weeds and rhizosphere microbial populations in rice established by system rice intensification (SRI) method. Treatments included: combinations of pre-emergence application (PE) of pyrazosulfuron-ethyl and early post-emergence application (EPoE) of bispyribac-sodium, integrated with cono weeding and hand weeding. The highest weed control efficiency (WCE) of 94.6% at 60 DAT and preservation of rhizosphere microbial populations were observed with bispyribac-sodium 30 g/ha EPoE at 15 DAT followed by (*fb*) cono weeding at 30 and 40 days after rice transplanting (DAT). In contrast, pyrazosulfuron-ethyl 25 g/ha 25 g/ha PE reduced microbial population. It is concluded that integrated weed management, comprising bispyribac-sodium 30 g/ha EPoE at 15 DAT *fb* cono weeding at 30 and 40 DAT effectively managed weeds and supported soil microbial health in rice established by SRI method.

Keywords: Actinomycetes, Bacteria, Bispyribac-sodium, Fungi, Microbial population, Transplanted rice, SRI, Weed management

INTRODUCTION

Rice (*Oryza sativa* L.) is a significant cereal crop that is extensively cultivated and serves as a primary food source in India. In India, rice is cultivated on 43.66 million hectares, yielding a total production of 118.87 million tons, with an average productivity of 2.72 t/ha. Weeds represent a significant biotic barrier that restricts yield, affecting growth and productivity through both competitive and non-competitive mechanisms (Rao *et al.* 2017; 2017a). The rice grain yield was reported to be severely reduced, due to weeds uncontrolled during the early the critical period of rice growth (Bhagavathi *et al.* 2023). Thus, weeds that appear in the initial phase of crop growth need to be managed to prevent competition during the critical period.

The use of pre-emergence herbicides is being used to control weeds emerged during early crop growth stage. However, weeds continue to emerge 10 to 20 days after pre-emergence herbicide application due to their adaptation and favourable

environment. Under such situation, early post-emergence herbicide application help managing the problem of late emerged weeds and provides improved weed control during the critical period (Dass *et al.* 2017). Herbicides are not detrimental, to rice and soil microbes when used at suggested rates and time and certain herbicides may enhance the growth and activity of the rhizosphere microflora. However, frequent use of herbicides can lead to a rise in herbicides resistant weed populations and potentially negatively impact the rhizosphere microflora community.

In system rice intensification (SRI) method of rice cultivation, weed control is achieved using cono weeder. However, lack of labour for operating cono weeders, rising labour costs and timely weeding during the initial stage of rice growth have made it necessary to employ herbicides for weed control in the SRI (Shekhawat *et al.* 2020). Studies on effect of integrating cono weeding along with herbicides and hand weeding under SRI are limited. Thus, this study was conducted with an objective to assess and identify effective integrated weed management options that includes herbicide, mechanical, and manual weeding, while studying their impact on weeds and the population of rhizosphere microflora in transplanted rice.

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MATERIALS AND METHODS

The experiment conducted during the *Kharif* seasons of 2022 and 2023 at the Experimental Farm of the School of Agriculture, Bharath Institute of Higher Education and Research (12.92080 N, 80.13060 E), Chennai, Tamil Nadu with nine treatments and three replications in a randomized block design. The tested treatments include: consisted of different combination of herbicide viz, pre-emergence application (PE) of pyrazosulfuron-ethyl 25 g/ha on 3 days of transplanting (DAT) + cono weeding at 30 and 40 DAT, pyrazosulfuron-ethyl 25 g/ha 3 DAT followed by (*fb*) hand weeding at 40 DAT, pyrazosulfuron-ethyl 25 g/ha 3 DAT *fb* cono weeding at 30 DAT and hand weeding at 40 DAT, early post-emergence application (EPOE) of bispyribac-sodium 30 g/ha 15 DAT *fb* cono weeding at 30 and 40 DAT, bispyribac sodium 30 g/ha EPOE on 15 DAT *fb* hand weeding at 40 DAT, bispyribac sodium 30 g/ha EPOE on 15 DAT *fb* cono weeding at 30 DAT and hand weeding at 40 DAT, hand weeding twice at 20 and 40 DAT, cono weeding at 10, 20, 30 and 40 DAT and unweeded control. The CO 51 crop variety for the experiment was cultivated during the *kharif* seasons of 2022 and 2023. To establish a nursery for SRI, seeds were sown at a rate of 8 kg/ha over an area of 100 m²/ha. Seedlings that were 18 days old were used for transplanting in the SRI method. A fertilizer application of 120:40:40 NPK kg/ha was utilized as the standard procedure for the experiment. According to the treatment plan, the necessary amount of herbicides was applied. Both pre-emergence and post-emergence herbicides were sprayed using a high-volume knapsack sprayer equipped with a flood jet nozzle, utilizing 500 liters of water/ha. Weed density and biomass were estimated using standard procedures. At 60 days after transplanting (DAT), the weed control efficiency (WCE) and weed index (WI) were calculated by using the formula given by Mani *et al.* (1973) and Gill and Vijayakumar (1966).

$$\text{WCE}(\%) = \frac{\text{Weed biomass in control plot} - \text{weed biomass in treated plot}}{\text{weed dry weight in control plot}} \times 100$$

$$\text{WI} = \frac{X - Y}{X} \times 100$$

Where,

X = Yield from plot with the minimum weeds (kg/ha)

Y = Yield in the respective treatment plot (kg/ha) for which the weed index to be calculated

Soil samples for microflora analysis were collected from the 0 to 15 cm topsoil at the initial stage and 20, 40, and 60 days after transplanting in all the plots across both cropping seasons. The soil samples were placed in 90 ml of deionized water at a ratio of 10 g. The mixture was stirred for 10 minutes and then allowed to settle for 5 minutes. Subsequently, 1 ml of the supernatant was diluted twofold and combined with the diluted water while keeping a constant temperature of 30°C. All samples were prepared in sets of three and used for counting microorganisms. The counts of viable microbes were assessed using the standard serial dilution and pour plating methods. The identification of bacteria and fungi was performed using soil extract agar medium (James 1958) and rose bengal agar medium (Parkinson *et al.* 1971). Kenknight's agar medium was utilized for counting actinomycetes (Wellington and Toth 1963). After creating separate microbial colonies under suitable incubation conditions, we counted the colonies and assessed the number of viable bacteria, fungi, and actinomycetes (represented as colony forming units, or cfu) per gram of dry soil weight by examining the soil dilutions (Nagamani *et al.* 2006).

RESULTS AND DISCUSSION

Effect on weeds

The dominant weed species found in the experimental field included *Echinochloa colona* and *Echinochloa crus-galli* among the grasses, *Cyperus difformis* among the sedges, and *Ammania baccifera* and *Eclipta alba* among the broad-leaved weeds in transplanted rice.

The integration bispyribac-sodium at 30 g/ha EPOE on 15 DAT *fb* cono weeding at 30 and 40 DAT recorded higher WCE at 60 DAT (94.6% and 91.6 % during 2022 and 2023, respectively) and lower WI (**Table 1**). The increased weed management efficiency during the crucial period of competition was observed with the integration of bispyribac-sodium application with cono weeding due to effective and broad-spectrum action of bispyribac-sodium against weeds which was supplemented with cono weeding and hand weeding confirming Nath *et al.* (2024). Unweeded control registered higher weed index of 51.97%. The use of herbicides for effective and broad-spectrum control of all emerged weeds during the early stages of crop growth, along with two subsequent cono weeding at 30 and 40 days after transplanting (DAT), resulted in efficient weed management and a weed-free environment throughout the crop's growth period. This reduced

Table 1. Effect of weed management treatments on weed control efficiency (%) and weed index at 60 DAT during Kharif 2022 and 2023

Treatment	Weed control efficiency (%)			Weed index
	Kharif 2022	Kharif 2023	Kharif 2022	Kharif 2023
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 and 40 DAT	91.8	87.6	10.22	10.36
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> HW at 40 DAT	91.6	87.1	10.9	11.0
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 DAT and HW on 40 DAT	86.5	84.2	13.12	12.65
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 and 40 DAT	94.6	91.6	0.00	0.00
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> HW on 40 DAT	94.0	91.2	4.23	5.21
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 DAT <i>fb</i> HW on 40 DAT	87.2	85.4	13.68	13.63
Hand weeding twice on 20 and 40 DAT	93.7	89.1	8.69	7.32
Cono weeding on 10, 20, 30 and 40 DAT	93.9	90.0	7.02	7.55
Unweeded control	-	-	59.41	61.32
LSD (p=0.05)	17.5	16.0	10.8	11.5

PE: pre-emergence application; EPoE: early post-emergence application; DAT: days of transplanting; *fb*: followed by; CW: cono weeding; HW: hand weeding

Table 2. Effect of weed management treatments on rhizosphere bacterial population in rice at 20, 40 and 60 DAT during Kharif 2022 and 2023

Treatment	Total bacterial population (CFU x 10 ⁵ /g dry weight of soil)							
	Kharif 2022				Kharif 2023			
	Initial day	20 DAT	40 DAT	60 DAT	Initial day	20 DAT	40 DAT	60 DAT
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 and 40 DAT	191	132	139	140	192	136	148	150
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> HW at 40 DAT	192	130	135	144	191	131	139	145
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 DAT and HW on 40 DAT	191	129	131	136	193	130	133	140
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 and 40 DAT	192	145	152	159	193	151	159	163
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> HW on 40 DAT	193	143	149	156	191	148	155	160
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 DAT <i>fb</i> HW on 40 DAT	192	133	140	142	193	145	150	156
Hand weeding twice on 20 and 40 DAT	195	175	182	185	193	173	181	184
Cono weeding on 10, 20, 30 and 40 DAT	191	177	186	188	191	175	187	190
Unweeded control	193	180	191	194	192	187	189	192
LSD (p=0.05)		14.2	14.6	14.9	-	12.6	12.1	12.5

PE: pre-emergence application; EPoE: early post-emergence application; DAT: days of transplanting; *fb*: followed by; CW: cono weeding; HW: hand weeding

Table 3. Effect of weed management treatments on rhizosphere fungal population in rice at 20, 40 and 60 DAT during Kharif 2022 and 2023

Treatment	Total fungal population (CFU x 10 ³ /g dry weight of soil)							
	Kharif 2022				Kharif 2023			
	Initial day	20 DAT	40 DAT	60 DAT	Initial day	20 DAT	40 DAT	60 DAT
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 and 40 DAT	19.5	14.2	14.9	15.7	19.6	15.3	16.4	17.6
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> HW at 40 DAT	20.4	13.9	14.6	15.3	19.5	14.0	15.1	16.6
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 DAT and HW on 40 DAT	20.3	13.8	14.5	15.1	19.9	13.4	14.1	15.9
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 and 40 DAT	20.1	17.1	17.9	18.5	19.6	17.5	18.3	20.8
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> HW on 40 DAT	19.8	16.8	17.4	18.1	20.1	16.9	17.6	19.2
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 DAT <i>fb</i> HW on 40 DAT	19.9	16.6	17.1	17.8	19.5	16.0	17.2	18.5
Hand weeding twice on 20 and 40 DAT	20.6	18.3	18.6	19.2	20.2	19.0	20.1	22.0
Cono weeding on 10, 20, 30 and 40 DAT	20.1	18.8	19.0	19.5	19.5	19.5	20.8	22.2
Unweeded control	19.9	19.5	20.3	21.2	20.2	20.2	21.5	22.8
LSD (p=0.05)	-	1.4	1.5	1.6	-	1.9	1.6	1.8

PE: pre-emergence application; EPoE: early post-emergence application; DAT: days of transplanting; *fb*: followed by; CW: cono weeding; HW: hand weeding

crop-weed competition and minimum nutrient removal by weeds which might have increased the capacity of nutrient uptake and enhanced the source and sink sizes which in turn increased the yield. The highest net profit and BCR (Table 5) were observed with bispyribac-sodium 30 g/ha EPoE combined with cono weeding at 30 and 40 DAT. This method was

followed by the combination of bispyribac-sodium 30 g/ha EPoE *fb* cono weeding at 30 DAT *fb* hand weeding at 40 DAT. The reduction in weed competition contributed to improved crop growth and higher rice grain yields. The next best was the practice of cono weeding four times at 10, 20, 30, and 40 DAT.

Table 4. Effect of weed management treatments on rhizosphere actinomycetes population in rice at 20, 40 and 60 DAT during Kharif 2022 and 2023

Treatment	Total actinomycetes population (CFU x 10 ³ /g dry weight of soil)							
	Kharif 2022				Kharif 2023			
	Initial day	20 DAT	40 DAT	60 DAT	Initial day	20 DAT	40 DAT	60 DAT
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 and 40 DAT	19.1	9.2	10.1	10.9	19.0	10.7	11.3	11.9
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> HW at 40 DAT	18.1	8.9	9.7	10.5	19.1	9.2	10.5	10.8
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 DAT and HW on 40 DAT	17.9	8.8	9.6	10.2	18.6	8.4	9.5	10.0
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 and 40 DAT	17.8	12.0	13.1	13.7	18.5	13.6	14.2	14.9
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> HW on 40 DAT	18.1	11.7	12.5	13.1	18.5	12.5	13.4	14.8
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 DAT <i>fb</i> HW on 40 DAT	18.5	11.5	12.1	12.8	19.1	11.9	12.8	13.4
Hand weeding twice on 20 and 40 DAT	17.9	17.9	18.5	19.1	19.4	17.5	18.0	19.1
Cono weeding on 10, 20, 30 and 40 DAT	18.5	18.2	18.7	19.4	19.2	18.0	18.3	19.4
Unweeded control	18.9	18.8	19.1	19.6	19.3	19.8	20.3	21.6
LSD (p=0.05)	-	1.2	1.4	1.5	-	1.1	1.6	1.3

PE: pre-emergence application; EPoE: early post-emergence application; DAT: days of transplanting; *fb*: followed by; CW: cono weeding; HW: hand weeding

Table 5. Effect of weed management treatments on yield and economics of rice at 20, 40 and 60 DAT during Kharif 2022 and 2023

Treatment	Kharif 2022				Kharif 2023			
	Grain yield (t/ha)	Straw yield (t/ha)	Net profit (x10 ³ Rs/ha)	BCR	Grain yield (t/ha)	Straw yield (t/ha)	Net profit (x10 ³ Rs/ha)	BCR
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 and 40 DAT	4.53	581	53.72	1.98	4.27	5.63	52.20	2.04
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> HW at 40 DAT	4.32	553	48.49	1.89	4.10	5.33	48.03	1.96
Pyrazosulfuron-ethyl 25 g/ha PE on 3 DAT <i>fb</i> CW on 30 DAT and HW on 40 DAT	4.03	501	41.20	1.75	3.92	4.96	43.33	1.86
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 and 40 DAT	5.32	682	72.54	2.33	5.18	6.51	73.08	2.46
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> HW on 40 DAT	5.28	671	71.24	2.30	4.98	6.50	69.09	2.38
Bispyribac-sodium 30 g/ha EPoE on 15 DAT <i>fb</i> CW on 30 DAT <i>fb</i> HW on 40 DAT	4.11	531	43.73	1.80	4.00	5.11	45.36	1.90
Hand weeding twice on 20 and 40 DAT	4.95	660	61.39	2.18	4.53	5.23	56.20	2.12
Cono weeding on 10, 20, 30 and 40 DAT	4.93	624	62.84	1.15	4.37	6.10	55.79	2.11
Unweeded control	2.98	407	17.33	1.38	2.51	3.85	11.74	1.23
LSD (p=0.05)	0.40	260	-	-	0.38	0.20	-	-

PE: pre-emergence application; EPoE: early post-emergence application; DAT: days of transplanting; *fb*: followed by; CW: cono weeding; HW: hand weeding

Rhizosphere microflora

Various weed management treatments significantly (p=0.05) affected the microbial communities during different growth stages of rice (Table 2,3,4). Unweeded control and cono weeding recorded the highest rhizosphere bacterial, fungal and actinomycetes population at 20, 40, 60 DAT in both the seasons due to none disturbance of soil without herbicide application, confirming the findings of Kundu *et al.* (2020). The improved soil aeration caused by cono weeding might have increased enzymatic activity as well as soil microbial population as observed by Pattanayak *et al.* (2022).

Among the treatments, bispyribac-sodium EPoE applied treatments recorded moderately higher rhizosphere bacterial, fungal and actinomycetes populations at 20, 40 and 60 DAT during both years. However, these microbial populations were lesser than those recorded under unweeded control.

Irrespective of herbicides, there was an increase in the population after 20 DAT. This might be due to degradation of herbicides in soil and reduced toxicity, which favored the increase in the microbial population, confirming Brochado *et al.* (2023), who observed that herbicides did not have harmful effects 30 days after the post-application.

However, the rhizosphere bacterial, fungal and actinomycetes population sharply declined in pyrazosulfuron-ethyl at 25 g/ha applied treatments when compared with the initial microflora population might be due to the toxicity of herbicides on microbes, confirming the findings of Bonnet *et al.* 2007, who also reported that herbicides have toxic effects on microorganisms before degradation. But among the different days of intervals at 20, 40 and 60 DAT, the level of microbial population gradually increased from 20 DAT as the days of pyrazosulfuron-ethyl application interval increased to 40 and 60 DAT.

It can be concluded that bispyribac-sodium 30 g/ha EPoE on 15 DAT *fb* cono weeding on 30 and 40 DAT managed weeds, during the critical period of crop-weed competition, in rice established by SRI method without any negative effects on the microbial population in the rice rhizosphere.

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RESEARCH ARTICLE

Evaluation of herbicides efficacy and selectivity for weed management in transplanted rice and the response of succeeding cowpea to herbicide residues

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ABSTRACT

A field experiment was undertaken in India's eastern sub-Himalayan plain during the *Kharif* seasons of 2021 and 2022 to evaluate various weed management options in transplanted rice and examine herbicides residual effects on succeeding cowpea crop. Among the treatments evaluated, early post-emergence application (EPoE) of bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha with a silicon-based non-ionic surfactant at 5 ml/l, recorded significantly higher reduction of weed density (83.3%), weed biomass (83.0%) with higher weed control efficiency (WCE) (85.3%) at 60 days after application (DAA). Bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha EPoE recorded higher benefit:cost ratio of 2.11 and outperformed manual weeding twice in terms of rice grain yield, straw yield, and net returns. Pyrazosulfuron-ethyl 15 g/ha EPoE was effective against broad-leaved weeds, while bispyribac-sodium 25 g/ha EPoE performance was better against grasses and sedges (WCE of 65-66%). The emergence, plant stand, growth, or yield of subsequently grown cowpea was unaffected by residues of herbicides sprayed in transplanted rice proving that all herbicide treatments tested were safe to crops in rice-cowpea cropping system.

Keywords: Bispyribac-sodium, Herbicide residues, Penoxsulam, Pyrazosulfuron-ethyl, Transplanted rice, Weed management, Cowpea

INTRODUCTION

Rice (*Oryza sativa* L.) is a crucial cereal crop worldwide and serves as a major staple for about half of the global population, with around 90% of its production occurring in Asia. In India, the saying "Rice is life" truly reflects its role in ensuring national food security and sustaining rural livelihoods, contributing nearly 70% of the daily caloric intake (Yogi *et al.* 2023). With an output of 124 million tons over an area of around 44 million hectares, the crop accounts for 21.5% of the world's rice production (DES 2024). However, to feed the world's anticipated 1.64 billion people by 2050, rice production must rise significantly while limiting environmental damage and making wise use of scarce resources like labour, water, land, and agrochemicals (Rao 2022; Ahmad *et al.* 2021). The weeds are major constraints in direct-

seeded rice (DSR) causing higher (14 to 100%) than in transplanted rice (TPR) (7 to 80%) (Rao *et al.* 2017). Although TPR provides partial weed suppression through standing water and improved nutrient availability (Choudhary *et al.* 2021), repeated weed flushes during the crop growth period result in severe competition for nutrients, moisture and light. Manual weeding, though effective, has become increasingly impractical due to labour scarcity, frequent rains and escalating wage rates during the critical period of crop-weed competition (Choudhary and Dixit 2018). Under these circumstances, the use of herbicides, either as premixes or as tank-mix combinations with different modes of action, has emerged as an efficient and cost-effective weed management strategy. Such combinations were reported to provide broader weed control, reduce herbicide load and improve economic returns. However, location-specific information on their efficacy remains limited. Thus, this study was conducted with an objective to assess the early post-emergence application (EPoE) of premix herbicide combinations efficacy to control weeds in transplanted rice and to examine herbicides residual effects of herbicides used in rice on succeeding cowpea.

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MATERIALS AND METHODS

A field experiment was carried out during the *Kharif* seasons of 2021 and 2022 at the Instructional Farm of Uttar Banga Krishi Viswavidyalaya, Pundibari, West Bengal (26°N latitude, 89°E longitude, and 43 m above mean sea level). The experimental soil had a sandy loam texture, a neutral response, and a medium fertility condition. A randomized block design (RBD), with nine treatments and three replications was used.

The tested treatments include: bispyribac-sodium 25 g/ha + pyrazosulfuron-ethyl 18.75 g/ha + silicon-based non-ionic surfactant 5 ml/l; bispyribac-sodium 30 g/ha + pyrazosulfuron-ethyl 22.5 g/ha + silicon-based non-ionic surfactant 5 ml/l; bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha + silicon-based non-ionic surfactant 5 ml/l; bispyribac-sodium 25 g/ha; pyrazosulfuron-ethyl 15 g/ha; triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha; penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha; untreated control and hand weeding twice. The rice variety MTU-7029 was grown under puddled and transplanted conditions. The cowpea variety Bidhan Sadabahar was cultivated as succeeding crop to assess residual effects of herbicides used in rice. Thirty days after seeding in a wet nursery, rice seedlings were transplanted with a spacing of 20 cm × 15 cm. At 14 days after transplanting (DAT), herbicides were sprayed as per the treatments using a backpack knapsack sprayer equipped with a flat-fan nozzle and a spray volume of 300-400 l/ha. Fertilizers at 120: 60: 60 kg/ha N: P: K were used. At the active tillering and panicle initiation stages, the remaining nitrogen was top-dressed in two equal splits, while full dosages of phosphorus, potassium, and half of the nitrogen were applied as basal. At 30, 45, and 60 days after application (DAA), weed density and weed dry weight (weed biomass) were measured by randomly placing three 0.25 m² quadrats in each plot. To quantify weed biomass, the weeds were identified based on their taxonomic characteristics, trimmed at ground level, sun-dried for 3-5 days, and then oven-dried at 70 ± 2°C until their weight remained constant. Weed control efficiency (WCE) and weed control index (WCI) were determined using weed biomass and grain yield data (Das 2008).

$$\text{WCE (\%)} = \frac{\text{Weed density in untreated plot} - \text{Weed density in treated plot}}{\text{Weed density in untreated plot}} \times 100$$

$$\text{WCI (\%)} = \frac{\text{Weed biomass in control} - \text{Weed biomass in treated plot}}{\text{Weed biomass in control}} \times 100$$

Data on weed density and biomass were subjected to square-root transformation ($\sqrt{x+0.5}$) before statistical analysis to normalize the variance. Yield attributes and grain yield were recorded at harvest. The cowpea (*Vigna unguiculata* L.) variety Bidhan Sadabahar was grown during the *rabi* seasons of both experimental years, following the harvest of *Kharif* season transplanted rice. The crop was sown one week after rice harvest after manual field preparation, without disturbing the original experimental layout. Sowing was carried out at a seed rate of 25 kg/ha. The residual effects of herbicide treatments on cowpea were assessed based on cowpea seedlings emergence percentage, plant stand, plant height, and seed yield. The data were analysed statistically by following the analysis of variance (ANOVA) as suggested by Gomez and Gomez (1984), and means were separated at $p < 0.05$ and adjusted with Fisher's protected least significant difference (LSD) test.

RESULTS AND DISCUSSION

Effect on weeds

The major weed species in the experimental plots were: *Echinochloa colona*, *Fimbristylis miliacea*, *Monochoria vaginalis*, *Eclipta alba*, and *Ludwigia parviflora*. Significant variation in weed management efficacy was recorded among treatments and growth stages (Table 1, 2 and 3). The hand-weeding caused complete elimination of all species (100%), while the untreated control recorded the highest weed density and biomass at all the crop growth stages. Among the herbicidal treatments, bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha (pre-mix) with a silicon-based non-ionic surfactant recorded the highest reductions of weed density (67.7% at 30 days after application (DAA), 68.8% at 45 DAA, and peaking at 83.3% at 60 DAA over the unweeded control) and weed biomass (average reductions of 77.8%, 78.5%, and 83.0% at 30, 45 and 60 DAA, respectively). The variation in weed density reduction at different rice growth stages indicates the herbicide formulation's prolonged residual efficacy and broad-spectrum activity under puddled transplanted conditions. This treatment resulted in higher control of *Fimbristylis miliacea* (67.6-83.8%) and *Eclipta alba* (75.5-88.2%) throughout the season, reflecting the combined strength of bispyribac-sodium on grasses and sedges such as *Echinochloa colona* and *Fimbristylis miliacea*, as reported earlier by Kaur *et al.* (2016) and Yadav *et al.* (2021), and pyrazosulfuron-ethyl's activity against broad-leaved aquatic weeds such as

Monochoria vaginalis and *Ludwigia parviflora*. A clear dose response was observed within the same premix. The intermediate dose of bispyribac-sodium 30 g/ha + pyrazosulfuron-ethyl 22.5 g/ha caused moderate reduction in weed density (averaging 56-58% across stages) and weed biomass (51.7%, 61.2%, and 65.3% at 30, 45 and 60 DAA, respectively), while the lowest rate of bispyribac-sodium 25 g/ha + pyrazosulfuron-ethyl 18.75 g/ha was markedly less effective, with weed density

reduction (of 21.4% at 30 DAA and 43.2% at 60 DAA) and weed biomass reduction of 27.7% at 30 DAA and 43.3% at 60 DAA. This highlights the importance of applying the recommended rate to ensure season-long control of the diverse transplanted rice weed flora that emerges at multiple flushes (Singh *et al.* 2017; Khippal *et al.* 2019). The superior performance of bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha across grasses, sedges, and broad-leaved weeds underscores the

Table 1. Effect of different weed management treatments on weed density(no./m²) and weed biomass(g/m²) at 30 DAA (pooled data)

Treatment	<i>Echinochloa crus-galli</i>		<i>Cyperus iria</i>		<i>Ludwigia parviflora</i>		<i>Fimbristylis miliacea</i>		<i>Monochoria vaginalis</i>	
	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	1.5(6.2)	3.5(12.2)	0.9(3.1)	3.1(9.5)	0.6(1.9)	3.8(13.4)	0.8(2.6)	3.2(10.3)	0.8(2.9)	3.5(12.2)
Bispyribac-sodium 30 g/ha+ pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	1.0(3.9)	2.8(7.9)	0.6(1.8)	2.5(6.3)	0.4(1.1)	3.1(9.5)	0.6(2.0)	2.6(6.9)	0.3(0.9)	2.8(7.9)
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	0.6(1.8)	1.9(3.7)	0.4(1.1)	1.7(2.9)	0.3(0.8)	2.1(4.2)	0.4(1.2)	1.8(3.2)	0.5(1.6)	1.9(3.7)
Bispyribac-sodium 25 g/ha	0.8(2.6)	2.9(8.5)	0.5(1.5)	2.6(6.9)	0.4(1.2)	3.3(10.9)	0.7(2.4)	2.7(7.5)	0.5(1.7)	2.9(8.5)
Pyrazosulfuron-ethyl 15 g/ha	0.7(2.3)	2.5(6.3)	0.5(1.5)	2.2(4.9)	0.4(1.2)	2.8(7.9)	0.6(2.1)	2.3(5.6)	0.5(1.7)	2.5(6.3)
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	1.2(4.9)	3.8(13.4)	0.7(2.3)	3.4(11.4)	0.6(2.0)	4.2(16.1)	0.9(3.4)	3.5(12.2)	0.5(1.7)	3.8(13.4)
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	0.9(3.3)	3.2(10.3)	0.6(2.0)	2.9(8.5)	0.5(1.7)	3.6(12.8)	0.8(2.9)	3.0(9.2)	0.3(0.9)	3.2(10.3)
Untreated control	1.6(7.1)	4.5(16.1)	0.9(3.4)	4.1(14.1)	0.7(2.5)	4.9(17.6)	1.1(4.9)	4.2(15.5)	0.9(3.4)	4.5(16.1)
Hand weeding twice	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)
LSD(p=0.05)	0.09	0.81	0.07	0.73	0.05	0.92	0.09	0.75	0.07	0.81

The values mentioned in parentheses are original; DAA = days after herbicide application

Table 2. Effect of different weed management treatments on density(no./m²) and weed biomass(g/m²) at 45 DAA (pooled data)

Treatment	<i>Echinochloa crus-galli</i>		<i>Cyperus iria</i>		<i>Ludwigia parviflora</i>		<i>Fimbristylis miliacea</i>		<i>Monochoria vaginalis</i>	
	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	2.3(13.9)	4.2(12.8)	1.6(6.9)	3.8(10.3)	1.1(3.9)	4.8(15.1)	1.7(8.1)	4.0(11.9)	1.1(3.9)	4.2(12.8)
Bispyribac-sodium 30 g/ha+ pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	1.8(9.1)	3.3(8.5)	1.2(4.5)	3.0(7.1)	0.9(3.2)	3.7(10.9)	1.4(6.1)	3.2(8.1)	0.9(3.2)	3.3(8.5)
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	1.0(3.5)	2.2(4.9)	0.8(2.5)	2.0(3.7)	0.6(2.0)	2.5(6.3)	0.9(3.2)	2.1(4.2)	0.7(2.3)	2.2(4.9)
Bispyribac-sodium 25 g/ha	1.5(6.9)	3.6(10.3)	1.1(4.1)	3.3(9.2)	0.8(2.9)	4.1(12.8)	1.3(5.9)	3.5(10.3)	0.9(3.5)	3.6(10.3)
Pyrazosulfuron 15 g/ha	1.3(5.9)	3.1(8.1)	1.0(3.5)	2.8(7.1)	0.7(2.5)	3.5(9.5)	1.2(4.9)	3.0(7.9)	0.8(2.9)	3.1(8.1)
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	2.1(12.1)	4.9(16.1)	1.5(6.5)	4.5(14.1)	1.0(3.9)	5.4(20.1)	1.8(9.1)	4.7(15.5)	1.0(3.9)	4.9(16.1)
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	1.9(10.1)	3.9(11.9)	1.3(5.1)	3.6(10.9)	0.9(3.5)	4.3(14.5)	1.6(7.9)	3.8(11.9)	0.9(3.5)	3.9(11.9)
Untreated control	2.6(17.9)	5.6(22.1)	1.8(9.1)	5.2(19.1)	1.2(4.9)	6.2(25.9)	2.3(15.1)	5.4(21.5)	1.2(4.9)	5.6(22.1)
Hand weeding twice	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)
LSD (p=0.05)	0.14	0.98	0.11	0.89	0.08	1.09	0.14	0.95	0.11	0.98

The values mentioned in parentheses are original; DAA = days after herbicide application

advantage of using a premix with complementary modes of action to ensure comprehensive control under transplanted rice ecosystems.

The combination of triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha was least effective option, with poor efficacy on *Ludwigia parviflora* and *Monochoria vaginalis*, indicating limited residual control under the tested conditions. Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha recorded intermediate performance, with average reduction in weed density of 48-55% and weed biomass of 35.9% and 49.8%, showing early-season activity on grasses

and sedges but limited residual control of broad-leaved weeds in later stages. The variation in the efficacy of individually applied herbicides on specific weeds highlights the need for herbicide selection based on predominant weed species in transplanted rice fields.

Weed indices

Weed control index (WCI) (Table 4) and weed control efficiency (WCE) (Table 5) varied significantly across treatments and crop growth stages, reflecting the differential efficacy of

Table 3. Effect of different weed management treatments on density (no./m²) and weed biomass (g/m²) at 60 DAA (pooled data)

Treatment	<i>Echinochloa crus-galli</i>		<i>Cyperus iria</i>		<i>Ludwigia parviflora</i>		<i>Fimbristylis miliacea</i>		<i>Monochoria vaginalis</i>	
	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass	Weed density	Weed biomass
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	5.29(27.5)	6.3(24.5)	3.10(9.6)	5.7(20.1)	2.16(4.7)	7.4(31.9)	3.37(11.3)	6.1(22.9)	2.58(6.6)	6.3(24.5)
Bispyribac-sodium 30 g/ha + pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	4.47(19.9)	4.9(14.9)	2.65(7.0)	4.4(12.8)	1.93(3.7)	5.6(19.1)	2.95(8.6)	4.7(13.9)	2.22(4.9)	4.9(14.9)
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	2.58(6.6)	3.4(7.1)	1.62(2.6)	3.1(6.3)	1.22(1.5)	3.9(9.5)	1.95(3.8)	3.3(7.1)	1.44(2.1)	3.4(7.1)
Bispyribac-sodium 25 g/ha	3.83(14.7)	5.4(18.3)	2.32(5.4)	4.9(15.1)	1.73(3.0)	6.3(24.5)	2.83(8.0)	5.2(17.3)	1.93(3.7)	5.4(18.3)
Pyrazosulfuron 15 g/ha	3.54(12.5)	4.6(13.4)	2.17(4.7)	4.2(11.9)	1.58(2.5)	5.2(17.3)	2.65(7.0)	4.4(12.8)	1.79(3.2)	4.6(13.4)
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	5.10(26.0)	7.4(33.5)	3.00(9.0)	6.7(28.1)	2.32(5.4)	8.5(43.1)	4.00(16.0)	7.2(32.5)	2.50(6.3)	7.4(33.5)
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	4.22(17.7)	5.8(21.5)	2.76(7.6)	5.3(18.3)	2.00(4.0)	6.7(28.1)	3.32(11.0)	5.6(20.1)	2.32(5.4)	5.8(21.5)
Untreated control	6.71(44.9)	8.3(42.5)	4.00(16.0)	7.6(36.5)	2.95(8.7)	9.6(56.3)	5.66(32.1)	8.1(40.5)	3.00(9.0)	8.3(42.5)
Hand weeding twice	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)	0.7(0.0)
LSD(p=0.05)	0.13	1.37	0.09	1.26	0.07	1.48	0.13	1.35	0.09	1.37

The values mentioned in parentheses are original; DAA = days after herbicide application

Table 4. Effect of different weed management treatments on weed control index (%) in transplanted rice (pooled data)

Treatment	<i>Echinochloa crus-galli</i>			<i>Cyperus iria</i>			<i>Ludwigia parviflora</i>			<i>Fimbristylis miliacea</i>			<i>Monochoria vaginalis</i>		
	30 DAA	45 DAA	60 DAA	30 DAA	45 DAA	60 DAA	30 DAA	45 DAA	60 DAA	30 DAA	45 DAA	60 DAA	30 DAA	45 DAA	60 DAA
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	24.2	42.1	42.4	32.6	46.1	44.9	23.9	41.7	25.8	33.5	44.7	43.2	24.2	42.1	42.4
Bispyribac-sodium 30 g/ha + pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	51.0	61.5	64.9	55.3	62.8	64.9	46.0	58.1	55.7	55.5	62.3	65.7	51.0	61.5	64.9
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	77.0	77.8	83.3	79.4	80.6	82.7	76.1	75.7	77.9	79.4	80.5	82.5	77.0	77.8	83.3
Bispyribac-sodium 25 g/ha	47.2	53.4	56.9	51.1	51.8	58.6	38.1	50.6	43.2	51.6	52.1	57.3	47.2	53.4	56.9
Pyrazosulfuron 15 g/ha	60.9	63.4	68.5	65.2	62.8	67.4	55.1	63.3	59.8	63.9	63.3	68.4	60.9	63.4	68.5
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	16.7	27.2	21.2	19.1	26.2	23.0	8.5	22.4	0.0	21.3	27.9	20.0	16.7	27.2	21.2
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	36.0	46.2	49.4	39.7	42.9	49.9	27.3	44.0	34.8	40.6	44.7	50.4	36.0	46.2	49.4
Untreated control	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hand weeding twice	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The values mentioned in parentheses are original; DAA = days after herbicide application

herbicides on transplanted rice weed flora. Among herbicidal treatments, the bispyribac sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha with a silicon-based surfactant was most effective, recording WCI of 77.8%, 78.5%, and 81.9%, and WCE of 79.1%, 68.6%, and 85.3% at 30, 45, and 60 DAA, respectively. Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha provided broad-spectrum control, controlling grasses: *Echinochloa colona* and *Fimbristylis miliacea* (>82% WCI; >85% WCE); and broad-leaved weeds: *Eclipta alba*, *Monochoria vaginalis*, and *Ludwigia parviflora* (WCE of 77-80%). Overall, bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha was effective on all weed groups and at different stages, demonstrating its suitability for integrated weed management in transplanted rice under mixed weed flora and labour-constrained conditions.

Effect on rice

Yield and yield attributing characters of rice (Table 6) exhibited marked variation in response to different weed management treatments. The untreated control consistently recorded the lowest values across all growth parameters. Due to uncontrolled weed competition during the crop’s critical growth stages, which restricted nutrient uptake, reduced tiller formation, and impaired assimilate translocation to the developing panicles. In the absence of weed control measures, intense competition between weeds and rice for essential resources such as light, nutrients, and water led to a significant reduction in rice biomass, plant height, number of tillers, and panicle size, owing to

decreased photosynthate assimilation (Mir *et al.* 2023). In contrast, hand weeding twice resulted in the highest values for most of the rice growth parameters, rice grain and straw yield. Due to vigorous rice vegetative growth in the absence of crop-weed competition. Among the herbicidal treatments, the bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha EPoE recorded higher plant height, panicles/hill, grains/panicle, and grain yield, which was statistically at par with hand weeding twice. The lower number of chaffy grains and higher panicle weight under this treatment reflected the positive effect of sustained weed suppression on grain setting and assimilate allocation towards reproductive organs. The high 1000-seed weight (29.91 g) further indicated improved nutrient availability and better photosynthate partitioning under reduced weed pressure.

Residual effect on succeeding cowpea

The data on the residual influence of herbicides applied in transplanted *Kharif* rice on the emergence, growth, and yield of the succeeding cowpea crop revealed (Table 6) that none of the recorded growth parameters of cowpea were significantly affected by herbicide treatments in rice. Emergence percentage in cowpea ranged from 78.2% under bispyribac-sodium 25 g/ha + pyrazosulfuron-ethyl 18.75 g/ha) to 84.2% in hand weeding twice, while plant stand varied between 18.2 and 22.2 plants/m². However, the differences were statistically non-significant, indicating that the herbicides used in transplanted rice did not leave any residues affecting seedling emergence or early crop establishment of cowpea.

Table 5. Effect of different weed management treatments on weed control efficiency (%) in transplanted rice (pooled data)

Treatment	<i>Echinochloa crus-galli</i>			<i>Cyperus iria</i>			<i>Ludwigia parviflora</i>			<i>Fimbristylis miliacea</i>			<i>Monochoria vaginalis</i>		
	30	45	60	30	45	60	30	45	60	30	45	60	30	45	60
	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA	DAA
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	12.7	22.3	38.7	73.5	24.2	68.2	76.0	20.4	55.3	18.4	46.4	64.7	17.7	20.4	73.3
Bispyribac-sodium 30 g/ha + pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	85.9	49.2	55.3	82.4	50.6	56.3	82.9	34.7	57.6	59.2	59.6	73.3	73.5	34.7	75.6
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	91.6	80.5	85.3	88.2	72.5	83.8	87.1	58.2	82.8	75.5	78.8	88.2	52.9	53.1	86.7
Bispyribac-sodium 25 g/ha	63.4	61.3	67.3	78.4	54.4	66.3	80.0	40.8	65.5	39.8	60.4	75.1	50.0	28.6	58.9
Pyrazosulfuron 15 g/ha	70.4	67.0	72.3	78.4	61.5	70.3	80.0	49.0	71.4	49.0	67.2	78.1	50.0	40.8	64.4
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	46.5	32.4	42.3	69.1	28.6	43.8	68.6	20.4	38.5	26.5	39.7	50.0	50.0	20.4	30.0
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	55.6	43.6	60.7	73.5	43.9	52.5	72.0	28.6	54.0	38.8	47.6	65.7	73.5	28.6	40.0
Untreated control	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hand weeding twice	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The values mentioned in parentheses are original; DAA = days after herbicide application

Table 6. Effect of different weed management treatments on growth and yield of transplanted rice and succeeding cowpea (pooled data)

Treatment	Growth and yield of rice									Growth and yield of cowpea			
	Plant height (cm)	No. of panicles/hill	No. of chaffy grains/panicle	No. of grains/panicle	Panicle length (cm)	Panicle weight (g)	1000 seed weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	Emergence (%)	Plant stand (no./m ²)	Plant height (cm)	Yield (t/ha)
Bispyribac-sodium 25 g/ha + pyrazosulfuron 18.75 g/ha + surfactant 5 ml/l	63.3	7.9	16.7	108.7	21.2	3.4	24.9	4.51	5.94	78.2	18.2	80.5	1.04
Bispyribac-sodium 30 g/ha + pyrazosulfuron 22.5 g/ha + surfactant 5 ml/l	66.7	9.0	14.7	116.3	23.1	3.6	26.8	5.44	7.04	81.5	20.5	86.2	1.14
Bispyribac-sodium 35 g/ha + pyrazosulfuron 26.25 g/ha + surfactant 5 ml/l	70.9	9.9	12.0	130.7	25.4	4.0	29.9	6.34	8.14	80.8	19.8	88.5	1.20
Bispyribac-sodium 25 g/ha	67.3	8.9	13.7	115.3	23.3	3.7	26.4	5.30	6.84	79.2	18.8	83.8	1.10
Pyrazosulfuron 15 g/ha	68.8	8.7	12.7	116.7	23.8	3.7	26.2	5.54	7.14	82.2	20.8	87.2	1.18
Triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha	69.4	8.6	12.3	118.7	24.3	3.8	25.9	5.24	6.74	80.2	19.2	82.8	1.06
Penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha	68.5	8.9	11.7	117.3	23.5	3.7	26.0	5.40	6.94	78.8	18.5	81.2	1.02
Untreated control	46.4	4.6	28.3	70.3	13.4	2.3	23.3	2.94	3.75	82.8	20.2	83.2	1.08
Hand weeding twice	72.6	10.9	9.3	138.3	26.6	4.2	31.3	6.54	8.34	84.2	22.2	90.2	1.22
LSD(p=0.05)	6.1	0.9	5.5	11.7	2.5	0.5	2.2	5.84	0.76	NS	NS	NS	NS

The values mentioned in parentheses are original

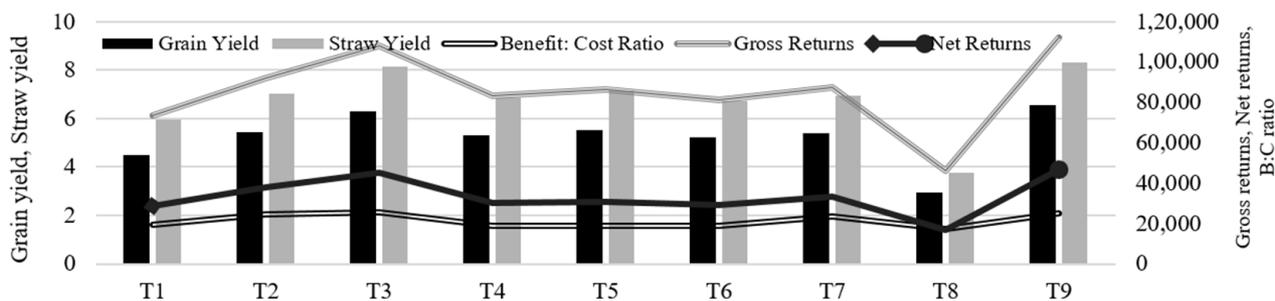


Figure 1. Effect of different weed management treatments on transplanted rice grain yield (t/ha), gross returns (₹/ha), net returns (₹/ha) and B:C ratio.

(T₁: bispyribac-sodium 25 g/ha + pyrazosulfuron-ethyl 18.75 g/ha + surfactant; T₂: bispyribac-sodium 30 g/ha + pyrazosulfuron-ethyl 22.5 g/ha + surfactant; T₃: bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha + surfactant; T₄: bispyribac-sodium 25 g/ha; T₅: pyrazosulfuron-ethyl 15 g/ha; T₆: triafamone 45 g/ha + ethoxysulfuron 22.5 g/ha; T₇: penoxsulam 22.95 g/ha + cyhalofop-butyl 114.75 g/ha; T₈: untreated control; T₉: hand weeding twice)

Plant height of cowpea and grain yield of cowpea followed a similar pattern with non-significant variation among treatments.

The differences were not statistically significant, suggesting that the herbicides used in rice either degraded rapidly under *Kharif* season soil moisture and temperature regimes or persisted at concentrations below phytotoxic thresholds for the succeeding cowpea. This aligns with earlier findings that most ALS-inhibiting herbicides, including bispyribac-sodium and pyrazosulfuron-ethyl, undergo rapid microbial and hydrolytic degradation in flooded rice soils, leaving negligible residues by the time of rabi or summer crop sowing. The overall results clearly demonstrate that the herbicide regimes evaluated for transplanted *Kharif* rice were safe to the succeeding crop cowpea, under the experimental soil and climatic conditions.

Economics

The analysis of weed management treatments in transplanted rice highlighted significant variations in cost-benefit (**Figure 1**). Hand weeding twice incurred the highest cultivation cost (₹ 65,390/ha) and yielded the highest gross returns (₹ 1,12,285/ha) and net returns (₹ 46,895/ha), with a B:C ratio of 2.07. The bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha (pre-mix) had a lower cultivation cost (₹ 63,190/ha) and achieved gross returns of ₹ 1,08,285/ha, net returns of ₹ 45,095/ha with highest B:C ratio of 2.11, demonstrating its profitability. The untreated control demonstrated the lowest economic performance. Thus, effective weed management using effective and economic treatment is essential for maximizing profitability.

It was concluded that bispyribac-sodium 35 g/ha + pyrazosulfuron-ethyl 26.25 g/ha with a silicon-based surfactant EPoE provided effective and economical broad-spectrum control of grasses, sedges, and broad-leaved weeds, with higher rice grain yield comparable to hand weeding twice and without adverse residual effects on the succeeding cowpea.

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RESEARCH ARTICLE

Wheat productivity response to preceding rice residue-retention and integrated weed management

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ABSTRACT

The sustainability of happy seeder (HS) sown wheat with preceding rice residue retention needs optimization of row spacing and integrated weed management. In this context, a study was conducted during *Rabi* seasons of 2020-21 and 2021-22 at Punjab Agricultural University, Ludhiana, India. The objective was to evaluate and identify the best option to realize higher wheat productivity and better weed management in wheat sown with happy seeder (HS) using varying row spacings in combination with retained preceding rice residues and integrated weed management treatments. The tested treatments include: wheat sown with happy seeder at row spacings (HS row spacing) of 18.25, 20.0 and 22.5 cm and weed control treatments including: unsprayed check, pre-plant application (PPA) of pyroxasulfone 127.5 g/ha, pendimethalin 1125 g/ha PPA, pendimethalin + metribuzin 962.5 g/ha PPA and post-emergence application (PoE) of metribuzin + clodinafop 270 g/ha. HS row spacing of 18.25 cm recorded *P. minor* density reduction of 16.7, 17.8% and 26.1, 27.1% and broad-leaved weeds density reduction of 22.1, 15.9% and 31.1, 27.8% at harvest, over HS row spacing of 20.0 and 22.5 cm, in 2020-21 and 2021-22, respectively. An increase in wheat grain yield of 24.9, 28.6% and 10.7, 16.3% was recorded with HS row spacing of 18.25 than HS row spacing of 20.0 and 22.5 cm during 2020-21 and 2021-22, respectively. Lower weed density (74.4%) and higher grain yield (82.9%) were recorded with metribuzin + clodinafop 270 g/ha compared to unsprayed check. Pendimethalin plus metribuzin 962.5 g/ha PPA by mixing with urea has provided greater control of diverse weed flora in wheat.

Keywords: Happy Seeder, Herbicide, Pendimethalin + metribuzin, Metribuzin + clodinafop, Rice residues, Wheat

INTRODUCTION

The rice-wheat cropping system is very important for the food security in the country due to its approximately 69% contribution to total government food procurement. The rice-wheat cropping system produces a large amount (7-10 t/ha) of crop residues. Total surplus residue in India was about 141 Mt/year and out of these 82 Mt of surplus was from cereals, 44 Mt was from rice and 24.5 Mt was from wheat crop (Kaur *et al.* 2022). Approximately 80% of rice crop residue produced yearly is being burnt within 20-25 days during late October and early November in the north western part of India. Residue burning results in loss of lot of nutrients, organic matter and causes air pollution problems which affect the human health (Gupta *et al.* 2004). Thus, farmers have to manage the huge tonnage of rice residue within a shorter window period of 15-20 days to sow the wheat crop in the stipulated time frame. Happy seeder technology provides the ability to drill wheat seeds directly into loose paddy residues (Sidhu *et al.* 2015). It does not

mix the stubbles into the soil rather retains the paddy stubbles (12-18 inches) on the soil surface and sow wheat at a depth of 2-3 inches, thereby reducing weed germination by 60-70% (Sidhu *et al.* 2007) as compared to conventional sowing method.

In rice-wheat cropping system, another major issue is weeds in wheat crop (Kaur *et al.* 2022). The yield losses due to weeds in this system are higher as compared to other cropping systems (Singh *et al.* 2005). Among all the different weeds, *Phalaris minor* is an important and troublesome grass weed of wheat. Moreover, *P. minor* has evolved resistance against ALS- and ACCase-inhibitors. The pre-emergence herbicides are effective against resistant *Phalaris* but their application in residue-retained wheat fields is a big challenge due to presence of heavy straw load on the soil surface. Post-emergence herbicides often fail to provide satisfactory control because the presence of paddy straw restricts their absorption by weeds. Multiple herbicide resistant population of *P. minor* is sensitive to pendimethalin (Chhokar *et al.* 2008). Metribuzin + clodinafop and pyroxasulfone provided effective weed control due to longer persistence of herbicide in the soil (Singh 2015) which ultimately helped to provide congenial

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environment to wheat for proper growth and development. Herbicides alone are unable to contain weeds despite their continuous use for longer periods. Thus, there is a need for development of integrated weed management (IWM) approaches for long-term management of weeds in wheat.

Optimal row spacing is also a common cultural approach for weed management and used to enhance the wheat productivity by optimizing tillering (Thind *et al.* 2019). Narrow row spacing can be exploited as a useful weed management tool as it smothers the weed flora (Marin and Weiner 2014; Ramesh *et al.* 2017). Earlier sowing with happy seeder at 22.5 cm row spacing was recommended by Punjab Agricultural University, Ludhiana. In this study, evaluation was done to identify the best row spacing and integrated weed management options to realize higher wheat productivity with effective management of herbicide resistant *P. minor* and other weeds in wheat sown with happy seeder while preceding rice residues are retained.

MATERIALS AND METHODS

The experiment was carried out at Research Farm, Punjab Agricultural University, Ludhiana (30° 54½N latitude and 75° 48½E longitude), India during 2020-21 and 2021-22. The area is characterized by sub-tropical semi-arid climate with very dry and hot summer during April to June, hot and humid monsoon during July to September, very cold winter during December-January and mild climate during February, March and October. Maximum temperature reaches above 47°C during summer months, while minimum temperature below 4°C accompanied by frost spells is quite common during the winter months of December and January. Average annual rainfall ranges between 500-750 mm. The soil of the experimental site was sandy loam in texture, normal in pH (6.7), normal in EC (0.14 dS/m), low in organic carbon (0.33%), low in available nitrogen (198 kg/ha), medium in available phosphorus (20.5 kg/ha), and medium in available potassium (157.5 kg/ha).

The field experiment was conducted in split plot design with three replications. Wheat sown with happy seeder at row spacings (HS row spacing) of 18.25, 20.0 and 22.5 cm in main plots and weed control treatments *i.e.*, unsprayed check, pre-plant application (PPA) of pyroxasulfone 127.5 g/ha, pendimethalin 1125 g/ha PPA, pendimethalin 35% + metribuzin 3.5% (pendimethalin + metribuzin) 962.5 g/ha PPA and post-emergence application (PoE) of metsulfuron 42% + clodinafop 12% (metribuzin + clodinafop) 270 g/ha in sub plots. Pre-plant herbicides were mixed with basal dose of urea (87.5

kg/ha) and broadcasted uniformly before sowing of wheat with happy seeder in the respective plots. After the harvesting of paddy crop, its residue (7.0 t/ha) were spread uniformly in the field. Wheat variety *PBW 725* was sown with 112.5 kg/ha seed on 3rd November 2020 and 15th November 2021. The recommended dose of 62.5 kg P/ha and 125 kg N/ha were applied. Full dose of phosphorus was applied at sowing time, while 87.5 kg/ha urea was applied (broadcast) before the sowing and remaining dose of nitrogen was applied in two equal splits, just before the first and second irrigation. The crop was harvested when the grains became hard and straw turned dry and brittle. During harvesting, bundles from each net plot were weighed to record the biological yield. After threshing, the grain yield obtained from each net plot was adjusted at 14% grain moisture. Straw yield from each plot was calculated by subtracting grain yield from biological yield.

For weeds data, weeds were counted as species-wise from two spots/plot with a quadrat of 0.5 m × 0.5 m at 60 DAS and at harvest. Weed biomass samples were cut at the collar portion of the plant, collected, sun dried and then dried in hot air oven at 60±2°C till constant weight was achieved. Weeds were separated out group-wise *i.e.*, grass and broad-leaved weeds. The weed control efficiency was calculated and expressed in percentage:

$$\text{Weed control efficiency} = \frac{\text{Weed biomass of unsprayed check} - \text{Weed biomass of treatment}}{\text{Weed biomass of unsprayed check}} \times 100$$

Leaf area index (LAI) at 60 DAS was recorded by using the Sun Scan Canopy Analyzer. Number of tillers were counted from the middle rows from the two randomly selected spots of 1m row length in each plot and later converted to tillers/m². Plant height was recorded from the 10 randomly selected plants from each treatment from base of plant to base of the fully opened leaves. The length of main ear was measured from the base to tip of floret excluding awns, and the averaged value of ear length was taken and from these ears, number of grains/ear was counted.

Data was analyzed using the GLM procedure in SAS 9.3 to evaluate differences between treatments; means were compared using Tukey's test for pair-wise comparison at p=0.05 (SAS 2011). LSD values were calculated to compare interaction means. Further, some interaction effects were interpreted by slicing out the effect of one factor in SAS. Weed density and biomass data were square-root-transformed before performing ANOVA because of high variance.

RESULTS AND DISCUSSION

Effect on weeds

Phalaris minor was the dominant grass weed in the experimental field. At 60 DAS, HS row spacing of 18.25 cm resulted in lower *P. minor* and broad-leaved weed density as compared to 20.0 cm and 22.5 cm during both the years of study (Table 1). HS row spacing of 18.25 cm recorded reduction of 16.7 and 17.8% & 26.1 and 27.1% in *P. minor* density and 22.1 and 15.9% and 31.1 and 27.8% in broad-leaved weeds than HS row spacing of 20.0 and 22.5 cm at harvest, in 2020-21 and 2021-22, respectively. It might be due to the fact that there was more number of crop plants per unit area in closer rows than the wider rows of 22.5 cm (Jamil *et al.* 2003) and wheat in narrow row spacing suppressed weeds more effectively as compared to wider row spacing (Brar and Walia 2010; Devi *et al.* 2018; Kaur *et al.* 2022).

Among the weed control treatments, at 60 DAS, metribuzin + clodinafop at 270 g/ha recorded significantly less mean *P. minor* and broad-leaved weed density being a broad-spectrum herbicide than pyroxasulfone 127.5 g/ha, pendimethalin + metribuzin at 962.5 g/ha, pendimethalin at 1125 g/ha and unsprayed check (Table 1). Similarly at harvest, there was reduction of 89.5 and 86.0% *P. minor* and broad-leaved weed density with metribuzin + clodinafop, 83.2 and 45.5% with pyroxasulfone, 73.6 and 69.2% with pendimethalin + metribuzin, 69.4 and 51.6% with pendimethalin than unsprayed check, respectively, when averaged both years. Kaur *et al.* (2017) reported earlier that pendimethalin + metribuzin resulted in a reduction of weed density of both grasses and broad-leaved weeds in wheat.

The interactive effect of happy seeder row spacing and weed control treatment on weed control at 60 DAS was significant in 2020-21 (Table 2). With an increase in wheat row spacing from 18.25 to 22.5 cm, *P. minor* density also increased at 60 DAS. The combination of pendimethalin + metribuzin with HS row spacing of 18.25 cm recorded statistically at par *P. minor* density with pyroxasulfone with HS row spacing of 20.0 cm and 22.5 cm. This indicated the greater suppression in weed density at 60 DAS with pre-mix pendimethalin + metribuzin or pyroxasulfone along with wheat narrow row spacing.

Weed biomass of *P. minor* and broad-leaved weeds was less with happy seeder sown spacing of 18.25 cm as compared to HS sown spacing of 20.0 cm and 22.5 cm at 60 DAS (Table 3). Similarly at harvest, HS sown row spacing of 18.25 cm resulted in reduction of biomass of *P. minor* (12.2 and 44.3%) and broad-leaved weeds (19.0 and 29.2%) than HS sown row spacing of 20.0 cm and 22.5 cm. Narrow row spacing provided the smothering effect which inhibits the weed germination and growth by reducing incoming radiant energy resulted in lesser biomass production of weeds as compared to wider spacing (Amare 2014; Mahajan and Brar 2002).

Among weed control treatments, metribuzin + clodinafop at 270 g/ha recorded less *P. minor* biomass in both years as compared to pyroxasulfone at 127.5 g/ha, pendimethalin + metribuzin at 962.5 g/ha, pendimethalin at 1125 g/ha as pre-plant. At harvest, higher reduction in *P. minor* and broad-leaved weed biomass was recorded with metribuzin + clodinafop, pyroxasulfone, pendimethalin + metribuzin and pendimethalin during both years confirming the findings of Qazizada *et al.* (2022) and

Table 1. Effect of happy seeder sown wheat row spacing and weed control treatments on density of *Phalaris minor* and broad-leaved weeds in wheat at 60 days after seeding (DAS) and at harvest during 2020-21 and 2021-22.

Treatment	<i>Phalaris minor</i> * (no./m ²)				Broad-leaved weeds* (no./m ²)			
	60 DAS		at harvest		60 DAS		at harvest	
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
<i>Happy seeder sown wheat row spacing (HS)</i>								
18.25 cm	3.70(17.3)	3.16(11.5)	3.98(18.4)	3.24(12.9)	5.17(31.4)	3.46(13.9)	5.74(37.3)	4.03(17.4)
20.0 cm	4.17(20.9)	3.44(13.5)	4.35(22.1)	3.62(15.7)	5.79(38.7)	4.00(17.7)	6.54(47.9)	4.41(20.7)
22.5 cm	4.15(21.7)	3.67(15.2)	4.59(24.9)	3.90(17.7)	6.13(43.6)	4.31(20.1)	6.99(54.1)	4.79(24.1)
LSD (p=0.05)	0.20	0.21	0.12	0.26	0.59	0.13	0.23	0.18
<i>Weed control (WC)</i>								
Unsprayed check	7.56(57.3)	6.36(39.6)	7.71(59.6)	6.42(41.3)	9.12(83.4)	5.82(34.0)	9.89(98.3)	6.09(37.2)
Pyroxasulfone 127.5 g/ha	3.08(9.6)	2.52(5.6)	3.20(10.3)	2.55(6.7)	6.49(42.4)	4.50(20.3)	7.07(50.2)	4.85(23.7)
Pendimethalin + metribuzin 962.5 g/ha	3.64(13.3)	3.20(9.3)	3.82(14.7)	3.42(11.9)	4.40(19.9)	3.33(11.2)	5.15(26.9)	3.84(14.9)
Pendimethalin 1125 g/ha	4.05(16.4)	3.46(11.1)	4.13(17.1)	3.70(13.8)	6.13(37.8)	4.07(16.7)	6.78(46.2)	4.4(19.4)
Metribuzin + clodinafop 270 g/ha	1.71(3.2)	1.57(1.6)	2.68(7.2)	1.84(3.4)	2.34(5.9)	1.9(3.9)	3.24(10.7)	2.85(8.3)
LSD (p=0.05)	0.26	0.33	0.15	0.22	0.48	0.18	0.18	0.22
<i>Interaction (HS x WC)</i>								
LSD (p=0.05)	S	NS	NS	NS	NS	NS	NS	NS

*Figures in parentheses are original means. Data were subjected to square root transformation

Ahirwal *et al.* (2020). Pendimethalin alone could not provide adequate control of *P. minor* but its mixture with other herbicides was very effective against *P. minor* and other weeds (Bayat and Zargar 2021). The interactive effect of happy seeder spacings and weed control treatments on weed biomass at 60 DAS and at harvest were not significant.

The highest *P. minor* weed control efficiency (WCE) (69.1 and 68.7%) and broad-leaved weeds WCE (61.5 and 52.8%) was recorded with HS sown row spacing of 18.25 cm during 2020-21 and 2021-22. Among weed control treatments, the highest WCE was recorded against *P. minor* and broad-

leaved weeds with metribuzin + clodinafop (88.65 and 83.7%) closely followed by pyroxasulfone (82.8 and 42.1%), pendimethalin + metribuzin (72.0 and 66.3%) and pendimethalin (67.8 and 50.2%) over unsprayed check (Table 3).

Effect on wheat

Happy seeder sown spacing of 18.25 cm produced higher grain yield (5.57 and 5.13 t/ha) than HS row spacing of 20.0 cm (5.03 and 4.13 t/ha) and 22.5 cm (4.46 and 3.99 t/ha) during 2020-21 and 2021-22, respectively. An increase of 24.9 & 28.6% and 12.8 & 10.5% grain yield was recorded in HS

Table 2. Interaction effect of happy seeder sown wheat row spacing and weed control treatments on *Phalaris minor* density (no./m²) in wheat at 60 DAS (2020-21)

Treatment	<i>Phalaris minor</i> density* (no./m ²)				
	Weed control (WC)				
	Unsprayed check	Pyroxasulfone 127.5 g/ha	Pendimethalin + metribuzin 962.5 g/ha	Pendimethalin 1125 g/ha	Metribuzin + clodinafop 270 g/ha
Happy seeder sown wheat row spacing (HS)					
18.25 cm	6.98 (48.7)	2.88 (8.3)	3.46 (12.0)	3.95 (15.7)	1.24 (1.7)
20.0 cm	7.72 (59.7)	3.11 (9.7)	3.64 (13.0)	4.08 (16.7)	2.35 (5.7)
22.5 cm	7.97 (63.7)	3.26 (10.7)	3.86 (15.0)	4.12 (17.0)	1.52 (2.3)
LSD (p=0.05)	HS = 0.20 WC= 0.26 HS × WC = 0.44				

*Figures in parentheses are original means. Data were subjected to square root transformation

Table 3. Effect of happy seeder sown wheat row spacing and weed control treatments on dry biomass of *Phalaris minor* and broad-leaved weeds in wheat and weed control efficiency during 2020-21 and 2021-22

Treatment	<i>Phalaris minor</i> biomass* (g/m ²)				Broad-leaved weeds biomass* (g/m ²)				Weed control efficiency (%)			
	60 DAS		at harvest		60 DAS		at harvest		<i>P. minor</i> at harvest		Broad-leaved weeds at harvest	
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
	<i>Happy seeder sown wheat row spacing (HS)</i>											
18.25 cm	2.22 (5.3)	2.27 (5.2)	5.45 (34.8)	4.47 (24.6)	2.52 (8.2)	1.49 (2.6)	6.66 (51.0)	4.72 (23.8)	69.1	68.7	61.5	52.8
20.0 cm	2.41 (5.8)	2.44 (6.0)	5.69 (37.4)	4.99 (29.8)	2.97 (10.8)	1.75 (3.5)	7.64 (65.6)	5.14 (28.2)	67.1	62.0	51.1	44.0
22.5 cm	2.40 (6.0)	2.58 (6.8)	6.90 (56.3)	5.37 (33.6)	3.25 (13.0)	1.88 (3.9)	8.17 (74.4)	5.54 (32.1)	50.0	95.4	44.5	36.3
LSD (p=0.05)	0.16	0.13	1.05	0.36	0.33	0.08	0.29	0.29	-	-	-	-
<i>Weed control (WC)</i>												
Unsprayed check	4.20 (16.9)	4.31 (17.7)	10.25 (112.5)	8.85 (78.5)	5.35 (28.9)	2.69 (7.3)	11.55 (134.1)	7.09 (50.4)	0.0	0.0	0.0	0.0
Pyroxasulfone 127.5 g/ha	1.83 (2.6)	1.84 (2.5)	4.47 (20.4)	3.51 (12.7)	2.92 (8.6)	1.91 (3.7)	8.40 (70.9)	5.62 (31.7)	81.9	83.8	47.1	37.1
Pendimethalin + metribuzin 962.5 g/ha	2.09 (3.5)	2.26 (4.2)	5.50 (30.5)	4.71 (22.6)	2.37 (5.9)	1.41 (2.0)	5.97 (36.3)	4.50 (20.4)	72.9	71.2	72.9	59.5
Pendimethalin 1125 g/ha	2.26 (4.5)	2.43 (5.0)	5.84 (34.6)	5.1 (26.2)	2.91 (8.7)	1.71 (3.0)	7.96 (63.9)	5.11 (26.2)	69.2	66.6	52.3	48.0
Metribuzin + clodinafop 270 g/ha	1.33 (0.9)	1.29 (0.7)	4.00 (16.2)	2.54 (6.5)	1.02 (1.2)	0.79 (0.7)	3.57 (13.1)	3.35 (11.5)	85.6	91.7	90.2	77.2
LSD (p=0.05)	0.20	0.21	1.21	0.3	0.38	0.09	0.36	0.24	-	-	-	-
<i>Interaction (HS x WC)</i>												
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	-	-	-	-

*Figures in parentheses are original means. Data were subjected to square root transformation

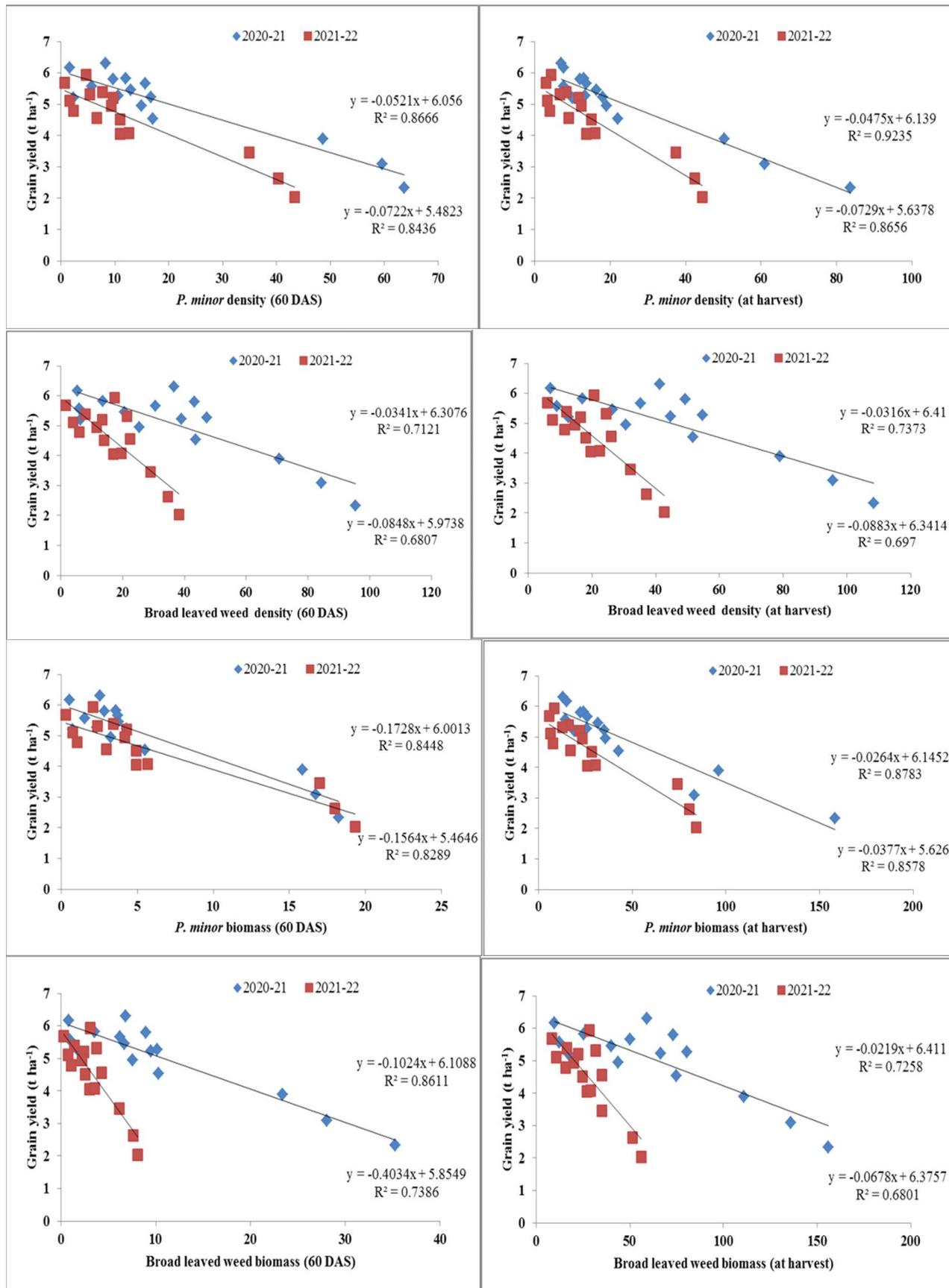


Figure 1. Relationship between grain yield and *Phalaris minor* and broad-leaved weed density (no./m²) and biomass (g/m²) in wheat

grain yield reduced linearly with an increase in *P. minor* density at 60 DAS and at harvest (**Figure 1**). *P. minor* infestation at 60 DAS caused 86.7 and 84.4% variation in grain yield during 2020-21 and 2021-22, respectively. Similarly, *P. minor* density accounted for 92.4 and 86.6% reduction at harvest during 2020-21 and 2021-22, respectively. Similarly, broad-leaved weed density caused 71.2 and 68.1% and 73.7 and 69.7% variation in grain yield of wheat at 60 DAS and at harvest during 2020-21 and 2021-22, respectively. *P. minor* biomass caused 84.5 and 82.9% and 87.8 and 85.8% variation in grain yield at 60 DAS and at harvest, during 2020-21 and 2021-22, respectively. Similarly, total broad-leaved weed biomass accounted for 86.1 and 73.9% and 72.6 and 68.0% variation in grain yield at 60 DAS and at harvest during 2020-21 and 2021-22, respectively (**Figure 1**).

Conclusion

Happy seeder sown wheat at 18.25 cm row to row spacing recorded less weed density and biomass, higher wheat yield attributes and grain yield than happy seeder sown wheat with 20.0 and 22.5 cm spacing. Pyroxasulfone 127.5 g/ha, pendimethalin 1125 g/ha or pendimethalin + metribuzin (pre-mix) 962.5 g/ha PPA by mixing with urea provided good control of diverse weed flora in wheat. Integration of narrow spacing (18.25 cm) with the above effective herbicides improved weed control and wheat productivity.

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RESEARCH ARTICLE

Performance of pyroxasulfone under simulated rainfall timings in wheat sown with super seeder

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ABSTRACT

A field experiment was conducted for two-years to study the effect of simulated rainfall on the efficacy of pre-emergence application (PE) of pyroxasulfone in the presence of varying amount of retained rice residues in wheat sown with Super seeder. The study was carried out at Punjab Agricultural University, Ludhiana, Punjab, India using factorial RCBD with treatments including: two levels of rice residue loads (0 and 7 t/ha), two doses of pyroxasulfone (127.5 and 191.25 g/ha) PE and three simulated rainfall timings (2, 5 and 10 days after sowing); and two standard controls: unsprayed and pyroxasulfone 127.5 g/ha. Incorporation of rice residue 7 t/ha recorded higher wheat dry matter accumulation and grain yield (3.8 and 3.7%) over residue removal during both the years. Pyroxasulfone 191.25 g/ha PE recorded significantly lower density and biomass of *Phalaris minor* compared to pyroxasulfone 127.5 g/ha PE. The tested simulated rainfall timings did not significantly affect the weed density, weed biomass and wheat grain yield and did not cause any phyto-toxicity due to pyroxasulfone.

Keywords: *Phalaris minor*, Pyroxasulfone, Rice residue incorporation, Simulated rainfall, Wheat

INTRODUCTION

Rice-wheat (RW) is a major cropping system of India that occupies an area of 9.2 m ha (Dhanda *et al.* 2022) and spread over the Indo-Gangetic Plains. Wheat (*Triticum aestivum* L.) is the world's major food crop that played an outstanding part in global food security. The fertile soils and irrigated ecologies in North-West part of India make it one of the most productive areas for wheat production in India. Wheat is serving as a staple food for 35% of the world's population (Grote *et al.* 2021) and providing 20% of the total dietary calories and proteins (Shiferaw *et al.* 2013). The sustainability of the RW system is becoming a big challenge due to multifarious problems like depleting groundwater, deterioration of surface water resources, degradation of soil health, reducing factor productivity, evolving herbicide-resistant weeds and burning of crop residue. In Punjab, 22 million tons of rice straw are produced annually (Anonymous 2024) from 3 million ha rice area in this intensively cultivated state. Thus, farmers have to manage this huge tonnage of rice residue within a shorter window period of 15-20 days

to sow their wheat crop in the stipulated time frame. To clear rice residue promptly, farmers resort to *in-situ* burning of rice straw and usually claim that it is the cheapest option for them to achieve the task of timely wheat sowing up to mid-November. However, late-sown wheat remains on the risk of terminal heat stress (Khan *et al.* 2021). Being a temperate C₃ crop, it gets prone to photorespiration losses during sudden rise in temperature (Sage and Kubien 2007), usually in mid-spring days. For management of rice residue, Super seeder, a tractor operated machine, is available in Punjab which incorporate paddy straw in soil, prepares the land, and sows the wheat seeds, simultaneously. This machine is very eco-friendly with environment by improving soil health (Singh *et al.* 2020). On the other hand, rice residue management is also one of the big opportunities to suppress weeds by laying these residues horizontally *in-situ* as mulch for weed suppression (Gill *et al.* 2025).

In RW cropping system, the yield losses due to weeds infestation are much higher as compared to any other cropping system (Singh *et al.* 2005). Among different weeds, *Phalaris minor* is the important grass weed of the wheat (Liu *et al.* 2021) that is highly competitive with wheat and causes much yield reductions approx. 25-80% (Chhokar and

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Malik 2002). Other wheat weeds, such as *Rumex dentatus* have developed resistance to ALS inhibitors (Chaudhary *et al.* 2021). Pre-emergence (PE) herbicides are effective to reduce the herbicide resistance development (Beckie and Hall 2014) but their efficacy depends on soil moisture and tillage (Ahirwal *et al.* 2020).

Crop residue can intercept some proportion of the PE herbicides that may result in the reduced weed control. Higher rate of PE herbicides must be needed for the adequate weed management due to binding of applied herbicides in high organic matter soil (Teasdale *et al.* 2003). The amount and time of rainfall also affect the herbicide wash-off from crop residue and its dissipation and movement. Rainfall can move the herbicide to proper depth of soil profile and also dissolve the herbicide to be available for plant absorption (Singh *et al.* 2002). Keeping these points in view, an experiment was conducted to study the effect of simulated rainfall on the efficacy of pre-emergence herbicide, pyroxasulfone, in the presence of varying amount of rice residue in wheat sown with Super seeder.

MATERIALS AND METHODS

A field experiment was conducted at Research Farm of Department of Agronomy, Punjab Agricultural University, Ludhiana (30° 54½N latitude and 75° 48½E longitude) during 2020-21 and 2021-22. This region is characterized by semi-arid with hot and dry early summer from March to June, hot and humid summer monsoon from July to September, mild winter from October to November and very cold winter from December to February. During the year, mean maximum and minimum temperatures shows significant fluctuations. The minimum temperature during *winter* season falls below 4°C while during *summer* season, temperature exceeds 38°C and many a time reaches 47°C. Average annual rainfall of Ludhiana district of Punjab is 759 mm, 75-80% of which is received during the monsoon period. The soil of the experimental site was sandy loam in texture, normal in reaction (pH 6.7), normal EC (0.14 dS/m), low in available organic carbon (0.33%), medium in available phosphorus (20.5 kg/ha) and medium in available potassium (157.5 kg/ha).

The experiment was conducted in a factorial RCBD with two levels of rice residue quantity retained in the field (rice residue load) (0 and 7 t/ha), pre-emergence application (PE) of pyroxasulfone at 127.5 and 191.25 g/ha and three simulated rainfall timings, *viz.* 2, 5, and 10 days after sowing (DAS). In

addition to the factorial treatments, two standard controls, *viz.* an unsprayed control and pyroxasulfone 127.5 g/ha PE were also included. Thus, a total of 14 treatments [(2 × 2 × 3) + 2] were tested and replicated thrice. Amount of simulated rainfall was calculated by taking last 10-year average (2010 to 2019) of November month *i.e.*, 4.94 mm (0, 0, 0, 4.6, 0, 0, 0, 7.0, 2.6, 35.2 mm). With rainfall of 10 mm, every square meter of field receives 0.01 m³ or 10 litre of rain water. So, with rainfall of 1mm, 1 square meter receives 1 liter of water. Simulated rainfall was given 4.94 mm (4.94 liters/m²). Gross plot area was 13.2 m² and 65.2 liters (4.94 × 13.2) of water was applied from 8 feet height standing on iron ladder with the help of plastic shower of 10 litre capacity. The droplet size of water was large and from 8 feet height it touches the soil with a force just like rain droplet. Sowing of wheat cv. *PBW 725* was done with Super seeder that incorporates paddy residue in soil at row spacing of 20 cm on 3rd and 1st November during 2020 and 2021, respectively. Pyroxasulfone PE was sprayed on the same day after sowing by using 500 litres/ha water. Recommended plant protection measures were taken against insect pests and diseases to ensure a healthy crop. Recommended dose of P, K and half N were applied at sowing while remaining half N was applied at first irrigation. Data on weeds was recorded with a quadrat (1 m × 1 m) from two spots in each of the plots at 90 DAS and at harvest. Different weed species were identified, counted and were cut at collar portion of the plants. The plants were then placed separately in brown paper bags to dry in the sun for 3-5 days. After the excess moisture was properly dried off, these paper bags were placed in an oven at 70±2°C for 72 hours until the weed samples achieved a constant weight, which was considered the weed biomass of the respective weed species. To analyse and interpret weed density and biomass, the average of both quadrats was converted into no./m² and g/m², respectively. The crop was harvested manually on 8th April, 2021 and 4th April, 2022. Observations on wheat seedling emergence count, leaf area index, dry matter accumulation and grain yield were recorded. Collected data were further analysed by using Proc GLM procedure of SAS version 9.4. To achieve normality in weed data distribution, square root transformation was performed before analysis. Economics of the treatments were carried out on the basis of income obtained from yield, cost incurred for each treatment and prevailing market prices.

RESULTS AND DISCUSSION

Effect on weeds

The dominant weed flora observed in experimental field comprised of grassy weed, *Phalaris minor* and broad-leaved weeds, *Rumex dentatus* and *Medicago denticulata*. The rice residue load has non-significant effect on *P. minor*, *R. dentatus* and *M. denticulata* density at 90 DAS and at harvest during both the years (Table 1). The *P. minor* density in pyroxasulfone 127.5 g/ha PE was significantly lower (91.1% and 89.7% at 90 DAS and 92.0% and 90.6% at harvest) as compared to unsprayed check in 2020-21 and 2021-22, respectively. The application of higher dose of pyroxasulfone 191.25 g/ha PE resulted in significantly better control of *P. minor* (24.0% and 15.9% at 90 DAS and 25.0% and 16.7% at harvest) as compared to recommended dose of pyroxasulfone in 2020-21 and 2021-22, respectively (Table 1). Similar observations were made by Kumar *et al.* (2013); Kaur *et al.* (2019); Kumar *et al.* (2021). But both doses of pyroxasulfone had non-significant effect on density of *R. dentatus* and *M. denticulata* at 90 DAS and at harvest during both years of study.

Pyroxasulfone herbicide was found to be less effective against *R. dentatus* and *M. denticulata* as compared to *P. minor*. Simulated rainfall at 2, 5 and 10 DAS did not produce significant effect on *P. minor*, *R. dentatus* and *M. denticulata* density during both years at 90 DAS and at harvest. The recommended dose of pyroxasulfone 127.5 g/ha PE has significantly lesser *P. minor* density than unsprayed check during both the years confirming observations of Johnson *et al.* (2018). The treatment mean indicates significantly less *P. minor*, *M. denticulata* and *R. dentatus* population at 90 DAS and at harvest than unsprayed check but statistically at par with recommended dose of herbicide without simulated rainfall during both years (Table 1).

At 90 DAS and at harvest, different rice residue load and simulated rainfall timings at 2, 5 and 10 DAS had non-significant effect on *P. minor*, *R. dentatus* and *M. denticulata* biomass during both years (Table 2). Pyroxasulfone 191.25 g/ha PE caused significantly lower biomass of *P. minor* (25.0% and 16.7% at 90 DAS and 25.0% and 10.0% at harvest in 2020-21 and 2021-22, respectively) than recommended rate of pyroxasulfone 127 g/ha. The treatment mean indicated significant reduction in

Table 1. Effect of treatments on weed density (at 90 DAS and at harvest) in Super seeder sown wheat

Treatment	Weed density*(no./m ²)											
	At 90 DAS					At harvest						
	Grass		Broad-leaved weeds			Grass		Broad-leaved weeds				
	<i>Phalaris minor</i>		<i>Medicago denticulata</i>	<i>Rumex dentatus</i>		<i>Phalaris minor</i>		<i>Medicago denticulata</i>	<i>Rumex dentatus</i>			
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22		
Rice residue load												
0 t/ha	2.27(4)	2.67(6)	4.78(22)	4.36(18)	2.00(3)	2.23(4)	2.07(3)	2.49(5)	4.54(19)	4.24(17)	1.85(2)	2.05(3)
7.0 t/ha	2.34(5)	2.75(7)	4.68(21)	4.31(18)	1.87(2)	2.14(4)	2.14(4)	2.54(5)	4.55(19)	4.19(17)	1.79(2)	2.00(3)
LSD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Pyroxasulfone doses												
Pyroxasulfone 127.5 g/ha	2.44(5)	2.81(7)	4.77(22)	4.38(18)	1.98(3)	2.20(4)	2.21(4)	2.57(6)	4.57(19)	4.26(17)	1.87(3)	2.05(3)
Pyroxasulfone 191.25 g/ha	2.17(4)	2.61(6)	4.68(21)	4.29(17)	1.89(3)	2.16(4)	2.00(3)	2.46(5)	4.52(19)	4.17(16)	1.77(2)	2.00(3)
LSD(p=0.05)	0.18	0.11	NS	NS	NS	NS	0.18	0.07	NS	NS	NS	NS
Simulated rainfall timings												
2 days after sowing	2.21(4)	2.62(6)	4.71(21)	4.33(18)	1.93(3)	2.19(4)	2.01(3)	2.48(5)	4.54(19)	4.21(17)	1.87(3)	2.06(3)
5 days after sowing	2.32(5)	2.73(7)	4.73(21)	4.33(18)	1.93(3)	2.20(4)	2.11(4)	2.51(5)	4.55(19)	4.20(17)	1.82(2)	2.03(3)
10 days after sowing	2.39(5)	2.78(7)	4.74(21)	4.35(18)	1.95(3)	2.15(4)	2.20(4)	2.55(6)	4.55(19)	4.22(17)	1.78(3)	1.99(3)
LSD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs Control												
Unsprayed	7.77(59)	8.28(68)	5.51(29)	4.93(23)	2.82(7)	3.16(9)	7.16(50)	8.06(64)	5.29(26)	4.76(22)	2.64(6)	2.89(7)
Pyroxasulfone 127.5 g/ha	2.51(5)	2.82(7)	4.79(22)	4.36(18)	1.80(2)	2.16(4)	2.16(4)	2.58(6)	4.54(19)	4.24(17)	1.82(2)	1.99(3)
LSD(p=0.05)	0.43	0.27	0.34	0.26	0.36	0.31	0.44	0.20	0.31	0.23	0.24	0.32
Treatment vs Control 1												
Treatment mean	2.31(4)	2.71(6)	4.73(21)	4.33(18)	1.93(3)	2.18(4)	2.11(4)	2.51(5)	4.55(19)	4.21(17)	1.82(2)	2.03(3)
Unsprayed	7.77(59)	8.28(68)	5.51(29)	4.93(23)	2.82(7)	3.16(9)	7.16(50)	8.00(64)	5.29(26)	4.76(22)	2.64(6)	2.89(7)
LSD(p=0.05)	0.21	0.12	0.15	0.12	0.15	0.14	0.20	0.09	0.14	0.11	0.11	0.14
Treatment vs Control 2												
Treatment mean	2.31(4)	2.71(6)	4.73(21)	4.33(18)	1.93(3)	2.18(4)	2.11(4)	2.51(5)	4.55(19)	4.21(17)	1.82(2)	2.03(3)
Pyroxasulfone 127.5 g/ha	2.51(5)	2.82(7)	4.79(22)	4.36(18)	1.80(3)	2.16(4)	2.16(4)	2.58(6)	4.54(19)	4.24(17)	1.82(2)	1.99(3)
LSD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Data were subjected to square root transformation. Parentheses are original values; DAS = days after seeding; NS = not significant

Table 2. Effect of treatments on weed biomass (at 90 DAS and at harvest) in Super seeder sown wheat

Treatment	Weed biomass*(g/m ²)											
	At 90 DAS						At harvest					
	Grass		Broad-leaved weeds				Grass		Broad-leaved weeds			
	<i>Phalaris minor</i>		<i>Medicago denticulata</i>		<i>Rumex dentatus</i>		<i>Phalaris minor</i>		<i>Medicago denticulata</i>		<i>Rumex dentatus</i>	
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
<i>Rice residue load</i>												
0 t/ha	2.07(3)	2.44(5)	3.89(14)	3.59(12)	1.84(2)	2.04(3)	2.69(6)	3.25(10)	5.27(27)	4.99(24)	2.10(3)	2.35(5)
7.0 t/ha	2.13(4)	2.52(5)	3.82(14)	3.56(12)	1.72(2)	1.96(3)	2.79(7)	3.32(10)	5.22(26)	4.93(23)	2.02(3)	2.30(4)
LSD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
<i>Pyroxasulfone doses</i>												
Pyroxasulfone 127.5 g/ha	2.21(4)	2.57(6)	3.89(14)	3.61(12)	1.82(2)	2.02(3)	2.89(8)	3.36(10)	5.27(27)	5.02(24)	2.11(4)	2.35(5)
Pyroxasulfone 191.25 g/ha	1.99(3)	2.39(5)	3.82(14)	3.54(12)	1.75(2)	1.99(3)	2.59(6)	3.21(9)	5.21(26)	4.91(23)	2.00(3)	2.30(4)
LSD(p=0.05)	0.16	0.09	NS	NS	NS	NS	0.27	0.10	NS	NS	NS	NS
<i>Simulated rainfall timings</i>												
2 days after sowing	2.01(3)	2.40(5)	3.84(14)	3.57(12)	1.78(2)	2.01(3)	2.60(6)	3.24(10)	5.23(26)	4.96(24)	2.11(4)	2.36(5)
5 days after sowing	2.12(4)	2.50(5)	3.86(14)	3.57(12)	1.78(2)	2.02(3)	2.74(7)	3.28(10)	5.25(27)	4.96(24)	2.05(3)	2.33(5)
10 days after sowing	2.17(4)	2.54(6)	3.87(14)	3.58(12)	1.79(2)	1.98(3)	2.89(7)	3.33(10)	5.26(27)	4.97(24)	2.00(3)	2.28(4)
LSD(p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
<i>Control vs Control</i>												
Unsprayed	6.92(47)	7.47(55)	4.48(19)	4.06(16)	3.45(11)	3.82(14)	9.82(96)	10.90(118)	6.11(36)	5.61(31)	3.89(14)	4.18(17)
Pyroxasulfone 127.5 g/ha	2.28(4)	2.58(6)	3.91(14)	3.59(12)	1.67(2)	1.98(3)	2.82(7)	3.38(10)	5.26(27)	5.00(24)	2.06(3)	2.28(4)
LSD(p=0.05)	0.37	0.24	0.27	0.21	0.30	0.27	0.63	0.27	0.31	0.28	0.29	0.40
<i>Treatment vs Control 1</i>												
Treatment mean	2.10(4)	2.48(5)	3.86(14)	3.57(12)	1.78(2)	2.00(3)	2.74(7)	3.28(10)	5.24(27)	4.96(24)	2.06(3)	2.32(5)
Unsprayed	6.92(47)	7.47(55)	4.48(19)	4.06(16)	3.45(11)	3.82(14)	9.82(96)	10.90(118)	6.11(36)	5.61(31)	3.89(14)	4.18(17)
LSD(p=0.05)	0.19	0.11	0.12	0.09	0.13	0.12	0.29	0.12	0.14	0.13	0.13	0.17
<i>Treatment vs Control 2</i>												
Treatment mean	2.10(4)	2.48(5)	3.86(14)	3.57(12)	1.78(2)	2.00(3)	2.74(7)	3.28(10)	5.24(27)	4.96(24)	2.06(3)	2.32(5)
Pyroxasulfone 127.5 g/ha	2.28(4)	2.58(6)	3.91(14)	3.59(12)	1.67(2)	1.98(3)	2.82(7)	3.38(10)	5.26(27)	5.00(24)	2.06(3)	2.28(4)
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Data were subjected to square root transformation. Parentheses are original values; DAS = days after seeding; NS = not significant

biomass of *P. minor* (91.5% and 90.9% at 90 DAS and 92.7% and 91.5% at harvest), *M. denticulata* (26.3% & 25.0% at 90 DAS and 25.0% and 22.6% at harvest) and *R. dentatus* (81.8% and 78.6% at 90 DAS and 78.6% and 70.6% at harvest) in 2020-21 and 2021-22, respectively over unsprayed check. No significant interactive effect of rice residue load, pyroxasulfone doses and timings of simulated rainfall was recorded at 90 DAS and at harvest in 2020-21 and 2021-22.

Effect on wheat growth and grain yield

The emerged wheat population was significantly higher with residue load of 0 t/ha (3.5% in 2020-21 and 6.1% in 2021-22) as compared to residue load of 7 t/ha. Reduced wheat seedling emergence under residue retention was due to physical obstruction/mechanical hindrance to the shoot emergence (Wuest *et al.* 2000; Ram *et al.* 2013). In 2020-21 and 2021-22, rice residue load 7 t/ha recorded significantly higher wheat leaf area index (8.4% and 8.9%, respectively) confirming Kaur (2022) and wheat dry matter accumulation (7.7% and 6.1%, respectively) over rice residue load of 0 t/ha. Both doses of pyroxasulfone, different treatment combination and simulated rainfall timings at 2, 5 and 10 DAS had non-

significant effect on wheat emergence count, LAI and dry matter accumulation during both years (Table 3). Rice residue load 7 t/ha recorded significantly higher wheat grain yield (3.8% in 2020-21 and 3.7% in 2021-22) over no residue as reported by Sharma and Acharya (2000).

The pyroxasulfone doses and simulated rainfall timings had non-significant effect on wheat grain yield during 2020-21 and 2021-22 (Table 3). Pyroxasulfone PE recorded significantly more wheat grain yield (44.8% in 2020-21 and 51.3% in 2021-22) than unsprayed control due to better control of weeds (Kaur *et al.* 2017).

Economics

All economic parameters were affected by different rice residue load, doses of pyroxasulfone and simulated rainfall timings. Rice residue load 7 t/ha recorded higher gross returns (5.1% and 4.6%), net returns (6.8% and 9.8%) and higher B:C as compared to no residues in 2020-21 and 2021-22, respectively (Table 4). The cost of cultivation was higher with rice residue load of 0 t/ha due to addition of residue removal cost over rice residue load of 7 t/ha. Pyroxasulfone doses and timings of simulated rainfall

Table 3. Effect of treatments on growth attributes and grain yield of Super seeder sown wheat

Treatment	Emergence count (no./m ²)		Leaf area index (LAI)		Dry matter accumulation (g/m ²)		Grain yield (t/ha)	
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
<i>Rice residue load</i>								
0 t/ha	130.1	131.9	5.84	5.74	1339	1249	5.85	5.14
7.0 t/ha	125.7	124.3	6.33	6.25	1442	1325	6.07	5.33
LSD (p=0.05)	4.1	4.5	0.22	0.24	39	15	0.15	0.15
<i>Pyroxasulfone doses</i>								
Pyroxasulfone 127.5 g/ha	128.6	129.2	6.06	5.96	1386	1271	5.90	5.17
Pyroxasulfone 191.25 g/ha	127.2	127.1	6.12	6.03	1395	1302	6.01	5.31
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
<i>Simulated rainfall timings</i>								
2 days after sowing	123.5	124.4	6.02	6.07	1394	1286	5.98	5.29
5 days after sowing	130.6	130.8	6.14	5.90	1394	1295	5.94	5.25
10 days after sowing	129.6	129.2	6.10	6.02	1384	1280	5.95	5.17
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
<i>Control vs Control</i>								
Unsprayed	128.3	130.0	5.37	5.27	925	770	4.05	3.36
Pyroxasulfone 127.5 g/ha	129.2	131.7	6.10	6.03	1335	1253	5.86	5.08
LSD (p=0.05)	NS	NS	0.57	0.55	91	33	0.38	0.35
<i>Treatment vs Control 1</i>								
Treatment mean	127.9	128.1	6.09	5.99	1391	1287	5.96	5.24
Unsprayed	128.3	130.0	5.37	5.27	925	770	4.05	3.36
LSD (p=0.05)	NS	NS	0.26	0.25	40	15	0.18	0.16
<i>Treatment vs Control 2</i>								
Treatment mean	127.9	128.1	6.09	5.99	1391	1287	5.96	5.24
Pyroxasulfone 127.5 g/ha	129.2	131.7	6.10	6.03	1335	1253	5.86	5.08
LSD (p=0.05)	NS	NS	NS	NS	42.02	15.26	NS	NS

Table 4. Effect of treatments on cost of cultivation, gross returns, net returns and benefit cost ratio of Super seeder sown wheat

Treatment	Gross returns (x10 ³ ₹/ha)		Cost of cultivation (x10 ³ ₹/ha)		Net Returns (x10 ³ ₹/ha)		Benefit: Cost	
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
<i>Rice residue load</i>								
0 t/ha	126.30	149.64	35.94	39.05	93.86	110.59	3.5	3.8
7.0 t/ha	132.70	156.52	32.44	35.05	100.26	121.47	4.1	4.5
<i>Pyroxasulfone doses</i>								
Pyroxasulfone 127.5 g/ha	128.18	151.66	37.19	39.80	95.74	111.86	3.4	3.8
Pyroxasulfone 191.25 g/ha	130.82	154.48	39.56	42.17	98.38	112.30	3.3	3.7
<i>Simulated rainfall timings</i>								
2 days after sowing	130.61	153.38	32.44	35.05	98.17	118.33	4.0	4.4
5 days after sowing	129.90	152.81	32.44	35.05	97.46	117.76	4.0	4.4
10 days after sowing	128.01	153.03	32.44	35.05	95.57	117.98	3.9	4.4
<i>Control vs Control</i>								
Unsprayed	85.46	103.70	32.44	35.05	53.02	68.65	2.6	3.0
Pyroxasulfone 127.5 g/ha	125.13	150.34	37.19	39.80	92.69	110.54	3.4	3.8

recorded similar B:C. Pyroxasulfone recorded higher gross returns and net returns as compared to unsprayed control during both years confirming Qazizada *et al.* (2022).

It may be concluded that rice residue load 7 t/ha incorporated using Super seeder recorded higher wheat grain yield, net returns and B:C. Pyroxasulfone 127.5 g/ha PE provided good control of *P. minor* and other broad-leaved weeds and produced higher wheat grain yield. However, simulated rainfall timings had no impact on weed biomass, productivity and economics of wheat.

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RESEARCH ARTICLE

Evaluation of isoxaflutole and thien carbazole–methyl for the management of itchgrass [*Rottboellia cochinchinensis* (Lour.) Clayton] in maize

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ABSTRACT

Itchgrass [*Rottboellia cochinchinensis* (Lour.) Clayton] is a highly invasive annual grass, ranked among the world's most troublesome weeds. In Karnataka, and in many other states of India, it poses a serious threat to maize and other crops across major maize-growing regions. As most herbicides have shown limited efficacy against this weed, a field study was conducted with an objective to study the effect of isoxaflutole + thien carbazole–methyl for the management of *R. cochinchinensis* in maize. It was conducted during Kharif 2023 and 2024 at a farmer's field in Pura village, Manchenahalli hobli, Gauribidanur taluk, Chikkaballapura district, Karnataka. The evaluated weed management options include: the pre-emergence application (PE) and early post-emergence application (EPoE) of isoxaflutole 225 g/L + thien carbazole–methyl 90 g/L SC (isoxaflutole + thien carbazole–methyl) (ready- mix) 73.12+29.25 and 90+36 g/ha, atrazine 50% WP (atrazine) 1000 g/ha PE, and topramezone 336 g/L w/v SC (topramezone) 33.6 g/ha + adjuvant 2 ml/L of water EPoE, hand weeded thrice at 20, 40, and 60 days after seeding (DAS) (weed-free) and an untreated control. The isoxaflutole + thien carbazole–methyl provided superior control of *R. cochinchinensis* and most associated weed species, except *Cyperus rotundus*. Isoxaflutole + thien carbazole–methyl (ready- mix) at both 73.12+29.25 and 90+36 g/ha PE and EPoE, consistently achieved the highest weed control efficiency, maximum maize grain and straw yield, and the lowest weed index demonstrating that it has a highly effective and promising option for managing *R. cochinchinensis* in maize.

Keywords: Itchgrass, Isoxaflutole, *Rottboellia cochinchinensis*, Thien carbazole–methyl, Maize, Weed management

INTRODUCTION

Maize (*Zea mays* L.) is one of the world's most important cereal crops, serving as a staple food, a vital feed source for livestock, and a key raw material for various agro-industries. In India, maize is cultivated on approximately 11.24 million hectares, producing 37.66 million tons with an average productivity of 3.35 t/ha (Anonymous 2023–24). In Karnataka produces 5.63 million tons of maize from an area of 1.97 million hectares and productivity of 2.89 t/ha, which is, notably lower than the national average maize productivity. Over the past decade, maize cultivation in Karnataka has expanded more rapidly than other crops, increasingly replacing traditional rainfed crops such as potato, tobacco, cotton, groundnut, finger millet (ragi), and sorghum (Prakash and Venkataramana 2023). A major challenge in the state's Karnataka's maize production is the prevalence of itchgrass (*Rottboellia cochinchinensis* (Lour.) Clayton) weed, particularly in the central districts. The regions in Karnataka, such

as Shimoga, Davangere, and Chitradurga with reported *R. cochinchinensis* infestations affecting nearly 50–60% of the sown area. *Rottboellia cochinchinensis*, a member of the family Poaceae, is among the most aggressive and destructive invasive weeds impacting tropical and subtropical agriculture. Native to the old world tropics, it has now spread extensively, infesting major crops such as maize, rice, sugarcane, soybean, cotton, and peanut (Anusha *et al.* 2023). Yield losses caused by this weed can be severe, up to 90% in maize (Pannacci and Onofri 2016), with other studies reporting reductions of 50% (Abouzienna *et al.* 2013) and 33.7% (Saady 2013) due to competition. Its invasiveness is attributed to strong competitive ability for essential resources and allelopathic effects (Kobayashi *et al.* 2008, Meksawat and Pornprom 2010). Moreover, its adaptability to diverse environmental conditions enhances its persistence, making management particularly difficult (Strahan *et al.* 2000, Fuhrer 2003, Chauhan 2012).

Rottboellia cochinchinensis infestations have persistently hindered maize from realizing its full yield potential. Weeds affect crop performance through intense competition and allelopathic interactions, leading to considerable reductions in both yield

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quantity and quality (Ramesh *et al.* 2017). Because *R. cochinchinensis* exhibits tolerance to several herbicides, its effective management remains a significant challenge. Hence, it is essential to develop sustainable management strategies aimed at minimizing yield losses by *R. cochinchinensis* and enhancing productivity in maize-based systems of Karnataka and similar agro-climatic regions. Hence, the present study was undertaken to identify an effective herbicide weed management option for controlling *R. cochinchinensis* in maize.

MATERIAL AND METHODS

The present experiment was conducted in association with University of Agricultural Sciences, Bengaluru during *Kharif* 2023 and 2024 under rainfed conditions at Pura village, Manchenahalli hobli, Gauribidanur taluk, Chikkaballapura district, Karnataka (13°56' N latitude and 77°55' E longitude). The mean monthly minimum temperature ranges from 17.2-19.9°C, while the mean monthly maximum temperature ranges from 26.3-30.9°C from August to December. During the experimental periods, the rainfall totals were 348.4 mm in 2023 and 912.8 mm in 2024. The experiment was laid out in a randomized block design (RBD) with eight treatments replicated three times. The tested treatments include: untreated control, pre-emergence application (PE) of isoxaflutole 225 g/L + thiencazone-methyl 90 g/L SC (ready-mix) (isoxaflutole + thiencazone-methyl) 73.12+29.25 g/ha and 90+36 g/ha, atrazine 50% WP (atrazine) 1000 g/ha PE, early post-emergence application (EPoE) of isoxaflutole + thiencazone-methyl 73.12+29.25 g/ha and 90+36 g/ha, topramezone 336 g/L w/v SC (topramezone) + adjuvant 33.6 g/ha + MSO 2 ml/L of water EPoE, and hand weeded thrice at 20, 40, and 60 days after seeding (DAS) (weed free). The maize crop was raised following the recommended package of practices with 20 kg/ha of Pioneer 3302 hybrid in the first week of August in both years. The crop was applied with 150 kg N, 75 kg P and 40 kg K/ha. The entire dose of P and K were applied at sowing, while N (urea) was top-dressed in three splits at 20, 40 DAS and tasseling stages. Herbicides were applied using a knapsack sprayer fitted with a flood-jet nozzle, delivering 500 L water/ha. Pre-emergence applications were made 3DAS, while early post-emergence applications were made on the 12th DAS. Species-wise weed counts were recorded before the EPoE herbicide spray, and subsequently at 28, 42 and 56 days after herbicide spray (DAHS). Species-wise weed dry weight (weed biomass) was measured at 56 DAHS from three randomly selected spots per plot

using a 1 m × 1 m quadrat. The collected data were statistically analyzed using square root transformation ($\sqrt{x+0.5}$). Weed density at 28, 42 and 56 DAHS and weed control efficiency (WCE) at 56 DAHS were computed. Crop yield was recorded at harvest, and the weed index was calculated accordingly.

Absolute Frequency (Prashanth *et al.* 2024)

$$\text{Absolute frequency} = \frac{\text{Number of quadrats in which species occurred}}{\text{Total number of quadrats}} \times 100$$

Relative frequency (Prashanth *et al.* 2024)

$$\text{Relative frequency} = \frac{\text{Absolute frequency of an individual species}}{\text{Absolute frequency of all species}} \times 100$$

Absolute density (Prashanth *et al.* 2024)

$$\text{Absolute density} = \frac{\text{Total number of individuals of a species}}{\text{Total number of quadrats}} \times 100$$

Weed control efficiency (WCE) was calculated using the formula (Singh *et al.* 2017)

$$\text{WCE}(\%) = \frac{\text{Dry weight of weeds in untreated control} - \text{Dry weight of weeds in treated plots}}{\text{Dry weight of weeds in untreated control}} \times 100$$

Relative weed density was computed using the formula (Krishnamurthy *et al.* 1975)

$$\text{Relative weed density} = \frac{\text{Number of individuals of same weed species}}{\text{Number of individuals of all weed species}} \times 100$$

Weed index (WI) was derived using the formula (Prachand *et al.* 2015)

$$\text{WI}(\%) = \frac{\text{Yield in weed free plot} - \text{Yield of the treatment}}{\text{Yield in weed free plot}} \times 100$$

The data collected over two years were subjected to analysis of variance (ANOVA) using the F-test, as outlined by Gomez and Gomez (1984). Significant differences among treatment means were compared using the least significant difference (LSD) at the 5% level of significance.

RESULTS AND DISCUSSION

Crop phyto-toxicity ratings

Visual observations on crop phyto-toxicity were recorded at 5, 10, 15, 20, and 25 DAHS. Symptoms such as yellowing, stunting, necrosis, epinasty, hyponasty, and leaf scorching were carefully monitored. No prominent phytotoxic effects were observed across treatments. However, application of

isoxaflutole + thien carbazole–methyl at higher dose (90+36 g/ha) PE and EPoE, induced slight yellowing of leaves up to 10 DAHS. This effect was transient, as the crop exhibited normal growth thereafter with no visible toxicity in the subsequent growth (Table 1). These observations are consistent with the findings of Idziak *et al.* (2022), who also reported the absence of phytotoxic effects in maize treated with isoxaflutole + thien carbazole–methyl at the recommended dose, either pre- or post-emergence.

Effect on weeds

A total of eight weed species were dominant in experimental plots. This included sedge: *Cyperus rotundus*; grasses: *Eleusine indica*, *Rottboellia cochinchinensis*, and *Dactyloctenium aegyptium* and broad-leaved weeds: *Portulaca oleracea*, *Ageratum conyzoides*, *Commelina benghalensis*, and *Parthenium hysterophorus*.

During both Kharif 2023 and 2024, *R. cochinchinensis* exhibited the highest relative frequency (69.44% and 66.55%, respectively), confirming its dominance within the weed community. Correspondingly, its absolute frequency, absolute density, and relative frequency values were the highest, further substantiating the predominance

of *R. cochinchinensis* in the experimental area (Figure 1). The next most dominant species, *Eleusine indica*, also recorded higher absolute frequencies of 87.50% and 91.67% during 2023 and 2024, respectively. A higher absolute frequency reflects a species’ widespread and consistent occurrence across the study area, providing valuable insights into its population dynamics, special distribution, and influence on overall weed community structure.

At 28 DAHS (Table 2) and 42 DAHS (Table 3), all herbicide-treated plots recorded significantly lower weed density of all weed species compared to the untreated control. At 28 DAHS, isoxaflutole + thien carbazole–methyl at 73.12+29.25 and 90+36 g/ha PE and EPoE reduced the density of *R. cochinchinensis* by 70.85% to 78.66% relative to the untreated check. In contrast, atrazine PE resulted in only 43.35% - 44.00% reduction. Isoxaflutole + thien carbazole–methyl EPoE consistently achieved lower weed density of all recorded species compared to pre-emergence treatments.

At 42 DAHS, isoxaflutole + thien carbazole–methyl, applied either PE or EPoE at 90+36 g/ha, recorded the lowest density of grasses and broad-leaved weeds. However, the density of *Cyperus*

Table 1. Phytotoxicity to maize due to pre-emergence application (PE) and early post-emergence application (EPoE) of isoxaflutole + thien carbazole–methyl (pooled data of two years)

Treatment	Yellowing DAHS					Stunting DAHS					Necrosis DAHS					Hyponasty / epinasty DAHS					Scorching DAHS				
	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
	Untreated control	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – PE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – PE	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – EPoE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – EPoE	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Based on 0-10 scale (0=00, 1=1-10%, 2=11-20%, 3=21-30%, 4=31-40%, 5=41-50%, 6=51-60%, 7=61-70%, 8=71-80%, 9=81-90%, 10=91-100%)

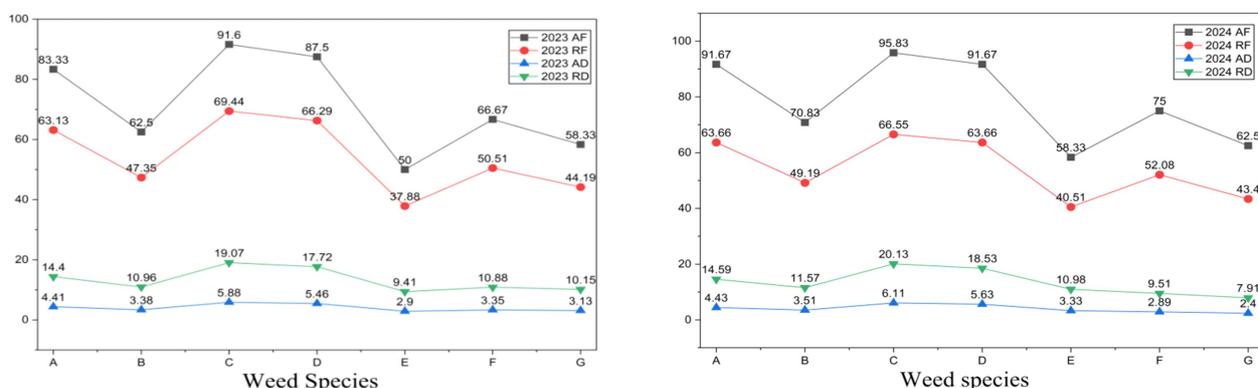


Figure 1. Initial absolute frequency, relative frequency, absolute density and relative density of individual weed species
 *AF- Absolute frequency (%), RF-Relative frequency (%), AD – Absolute density, RD- Relative density (%), A – *Cyperus rotundus*, B – *Dactyloctenium aegyptium*, C – *Rottboellia cochinchinensis*, D – *Eleusine indica*, E – *Commelina benghalensis*, F – *Portulaca oleracea*, G – *Ageratum conyzoides*

Table 2. Effect of different herbicides on major weed species density (no./m²) at 28 days after herbicide application in maize (pooled data Kharif 2023 and 2024)

Treatment	C. <i>rotundus</i>	D. <i>aegyptium</i>	R. <i>cochinchinensis</i>	E. <i>indica</i>	C. <i>benghalensis</i>	P. <i>oleracea</i>	A. <i>conyzoides</i>	P. <i>hysterophorus</i>
Untreated control	4.55 (20.21)*	4.52 (20.00)	5.45 (29.20)	4.43 (19.11)	4.18 (17.00)	4.05 (15.96)	4.18 (17.04)	3.48 (11.68)
Isoxaflutole + thien carbazono–methyl 73.12+29.25 g/ha – PE	3.37 (10.87)	3.14 (9.44)	3.00 (8.51)	3.39 (11.00)	2.83 (7.67)	2.79 (7.30)	2.77 (7.18)	2.48 (5.65)
Isoxaflutole + thien carbazono–methyl 90+36 g/ha – PE	3.18 (9.65)	2.99 (8.43)	2.82 (7.49)	3.08 (9.00)	2.73 (7.00)	2.52 (5.94)	2.51 (5.83)	2.23 (4.49)
Atrazine - PE 1000 g/ha	3.50 (11.80)	3.23 (9.92)	4.12 (16.54)	3.41 (11.11)	2.96 (8.33)	2.89 (7.83)	3.02 (8.60)	2.60 (6.29)
Isoxaflutole + thien carbazono–methyl 73.12+29.25 g/ha – EPoE	3.13 (9.29)	2.91 (7.95)	2.76 (7.12)	3.06 (8.89)	2.55 (6.00)	2.48 (5.84)	2.59 (6.23)	2.25 (4.56)
Isoxaflutole + thien carbazono–methyl 90+36 g/ha – EPoE	2.96 (8.27)	2.82 (7.45)	2.59 (6.23)	3.03 (8.67)	2.60 (6.33)	2.37 (5.29)	2.50 (5.74)	2.06 (3.76)
Topramezone + adjuvant 33.6 g/ha + MSO 2 ml/L of water -EPoE	3.36 (10.83)	3.12 (9.23)	4.10 (16.35)	3.37 (10.89)	2.90 (8.00)	2.83 (7.54)	2.81 (7.42)	2.49 (5.72)
Hand weeding - 20, 40 and 60 days after seeding (weed free)	1.64 (2.20)	1.61 (2.35)	1.80 (2.75)	1.78 (2.67)	1.22 (1.00)	1.77 (2.76)	1.80 (2.75)	1.80 (2.86)
LSD (p=0.05)	0.30	0.48	0.24	0.28	0.36	0.43	0.24	0.35

* Figures in the parentheses are original value and outside values are square root transformed at $\sqrt{x+0.5}$; PE = pre-emergence application; EPoE = early post-emergence application

Table 3. Effect of different herbicides on major weed species density (no./m²) at 42 days after herbicide application in maize (pooled data Kharif 2023 and 2024)

Treatment	C. <i>rotundus</i>	D. <i>aegyptium</i>	R. <i>cochinchinensis</i>	E. <i>indica</i>	C. <i>benghalensis</i>	P. <i>oleracea</i>	A. <i>conyzoides</i>	P. <i>hysterophorus</i>
Untreated control	4.96 (24.40)*	4.55 (20.26)	5.58 (30.70)	4.64 (21.04)	4.45 (19.33)	4.19 (17.11)	4.19 (17.07)	3.61 (12.62)
Isoxaflutole + thien carbazono–methyl 73.12+29.25 g/ha – PE	4.20 (17.17)	3.21 (9.82)	3.07 (8.95)	3.46 (11.47)	3.29 (10.33)	2.84 (7.57)	2.80 (7.40)	2.53 (5.93)
Isoxaflutole + thien carbazono–methyl 90+36 g/ha – PE	4.11 (16.48)	3.05 (8.82)	2.87 (7.77)	3.25 (10.10)	3.02 (8.67)	2.64 (6.49)	2.56 (6.05)	2.37 (5.10)
Atrazine - PE 1000 g/ha	4.34 (18.36)	3.33 (10.64)	4.46 (19.44)	3.59 (12.41)	3.29 (10.33)	2.98 (8.38)	3.09 (9.04)	2.74 (7.01)
Isoxaflutole + thien carbazono–methyl 73.12+29.25 g/ha – EPoE	4.06 (15.96)	2.95 (8.23)	2.85 (7.62)	3.27 (10.23)	3.12 (9.33)	2.58 (6.23)	2.68 (6.67)	2.33 (4.95)
Isoxaflutole + thien carbazono–methyl 90+36 g/ha – EPoE	3.98 (15.44)	2.89 (7.89)	2.71 (6.90)	3.06 (8.88)	3.01 (8.67)	2.49 (5.68)	2.56 (6.07)	2.19 (4.31)
Topramezone + adjuvant 33.6 g/ha+ MSO 2 ml/L of water -EPoE	4.19 (17.15)	3.24 (10.01)	4.27 (17.90)	3.48 (11.72)	3.69 (13.33)	2.87 (7.76)	2.97 (8.36)	2.63 (6.44)
Hand weeding - 20, 40 and 60 days after seeding (weed free)	1.33 (1.30)	1.26 (1.08)	1.36 (1.36)	1.53 (1.86)	1.58 (2.00)	1.36 (1.36)	1.52 (1.86)	1.65 (2.24)
LSD (p=0.05)	0.40	0.24	0.36	0.28	0.53	0.21	0.29	0.34

*Figures in the parentheses are original value and outside values are square root transformed at $\sqrt{x+0.5}$
PE = pre-emergence application; EPoE = early post-emergence application

rotundus showed minimal variation across treatments, indicating limited efficacy of the herbicide mixture against the species. Overall, the findings demonstrated the superior performance of isoxaflutole + thien carbazono–methyl, particularly with EPoE, for effective control of diverse weed flora, including *R. cochinchinensis*.

Pooled analysis indicated that weed biomass was significantly influenced by different herbicidal treatments (Table 4). At 56 DAHS, the lowest biomass of *R. cochinchinensis* was recorded in isoxaflutole + thien carbazono–methyl 73.12+29.25 or 90+36 g/ha PE, corresponding to a 7.0% - 17.6% reduction compared with atrazine. The same herbicide mixture EPoE reduced *R. cochinchinensis* biomass by 2.34% - 13.23% relative to atrazine.

Overall, herbicidal mixtures effectively suppressed weed growth and infestation, leading to a substantial reduction in weed biomass as reported by Patel *et al.* (2006).

Total weed biomass was also significantly influenced by herbicide treatments (Figure 2). At 56 DAHS, isoxaflutole + thien carbazono–methyl 73.12+29.25 g/ha and 90+36 g/ha EPoE recorded the lowest weed biomass. Aref *et al.* (2017) observed significant reductions in grassy weed biomass in maize with isoxaflutole + thien carbazono–methyl.

Weed control efficiency (WCE) for individual weed species was calculated based on their dry weight at 56 DAHS (Table 5). For *R. cochinchinensis*, WCE exceeded 90% with isoxaflutole + thien carbazono–methyl 73.12+29.25 g/

Table 4. Effect of different herbicides on major weed dry weight (g/m²) at 56 days after herbicide application in maize (pooled data Kharif 2023 and 2024)

Treatment	<i>C. rotundus</i>	<i>D. aegyptium</i>	<i>R. cochinchinensis</i>	<i>E. indica</i>	<i>C. benghalensis</i>	<i>P. oleracea</i>	<i>A. conyzoides</i>	<i>P. hysterophorus</i>
Untreated control	3.85 (14.45)	4.12 (16.44)	6.83 (46.18)	4.35 (18.45)	4.82 (22.75)	4.70 (21.59)	4.27 (17.82)	3.63 (12.67)
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – PE	3.22 (9.90)	2.34 (5.01)	2.82 (7.49)	2.27 (4.69)	2.55 (6.02)	2.50 (5.75)	2.33 (4.96)	2.08 (3.82)
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – PE	2.85 (7.69)	2.24 (4.50)	2.15 (4.15)	2.18 (4.24)	2.49 (5.70)	2.37 (5.10)	2.11 (3.96)	1.93 (3.23)
Atrazine - PE 1000 g/ha	3.07 (8.93)	2.55 (5.98)	3.57 (12.28)	2.59 (6.21)	2.88 (7.82)	3.00 (8.51)	2.57 (6.11)	2.30 (4.81)
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – EPoE	2.71 (6.86)	2.16 (4.16)	2.13 (4.02)	2.11 (3.95)	2.31 (4.84)	2.26 (4.63)	2.07 (3.81)	1.85 (2.91)
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – EPoE	2.55 (6.01)	2.11 (3.96)	2.03 (3.61)	2.07 (3.80)	2.24 (4.54)	2.21 (4.38)	2.02 (3.56)	1.76 (2.61)
Topramezone + adjuvant 33.6 g/ha+ MSO 2 ml/L of water -EPoE	3.19 (9.73)	2.36 (5.08)	3.20 (9.72)	2.30 (4.87)	2.53 (5.92)	2.51 (5.78)	2.31 (4.84)	2.00 (3.49)
Hand weeding - 20, 40 and 60 days after seeding (weed free)	0.87 (0.26)	1.08 (0.66)	1.15 (0.82)	1.24 (1.06)	1.56 (1.95)	1.37 (1.39)	1.12 (0.75)	1.16 (0.86)
LSD (p=0.05)	NS	0.11	0.19	0.29	0.17	0.15	0.22	0.16

Table 5. Effect of weed management practices on weed control efficiency at 56 days after herbicide application, grain yield and weed index in maize (pooled data Kharif 2023 and 2024)

Treatment	Weed control efficiency (%)								Grain yield (t/ha)	Weed index (%)
	<i>C. rotundus</i>	<i>D. aegyptium</i>	<i>R. cochinchinensis</i>	<i>E. indica</i>	<i>C. benghalensis</i>	<i>P. oleracea</i>	<i>A. conyzoides</i>	<i>P. hysterophorus</i>		
Untreated control	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.09	40.79
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – PE	31.48	69.54	83.78	74.61	73.54	73.38	72.18	69.89	7.40	13.91
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – PE	46.79	72.61	91.02	77.04	74.93	76.36	77.77	74.51	7.86	8.59
Atrazine - PE 1000 g/ha	38.21	63.63	73.42	66.37	65.63	60.59	65.70	62.08	6.68	22.34
Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha – EPoE	52.51	74.73	91.29	78.60	78.73	78.55	78.65	77.06	7.87	8.51
Isoxaflutole + thien carbazole–methyl 90+36 g/ha – EPoE	58.41	75.89	92.18	79.41	80.04	79.73	80.00	79.44	7.91	8.02
Topramezone + adjuvant 33.6 g/ha+ MSO 2 ml/L of water -EPoE	32.65	69.11	78.95	73.59	73.99	73.24	72.82	72.49	6.98	18.88
Hand weeding - 20, 40 and 60 days after seeding (weed free)	98.19	95.99	98.23	94.24	91.41	93.55	95.79	93.25	8.60	0.00

*PE = pre-emergence application; EPoE = early post-emergence application

ha and 90+36 g/ha PE and EPoE. In contrast, atrazine exhibited comparatively lower efficiency in managing all weed species. For the remaining weed species, the pre-mixed formulation of isoxaflutole + thien carbazole–methyl also achieved higher WCE values, ranging from 58.41-80.04% (Figure 3). However, its efficiency against *Cyperus rotundus* remained below 60%, indicating limited control of this species as reported by Idziak *et al.* (2022).

Effect on maize

Isoxaflutole + thien carbazole–methyl 90 + 36 g/ha PE and EPoE resulted in significantly higher maize grain yield (Table 5). Next best was same herbicide at 73.12 + 29.25 g/ha, compared to other treatments confirming the results of Stephenson and Bond (2012) in maize and Idziak *et al.* (2022) in sweet corn.

The weed index, representing the reduction in crop yield due to weed interference compared to the

weed-free treatment, was highest under the weedy check (40.79%). Conversely, the lowest weed index values (8.02% - 13.91%) were recorded with isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha and 90+36 g/ha PE and EPoE. The reduced weed index under these treatments attributed to higher maize yields which was achieved due to effective control of *R. cochinchinensis* and other associated weed species.

Conclusions

Isoxaflutole + thien carbazole–methyl 73.12+29.25 g/ha and 90+36 g/ha PE and EPoE effectively controlled *R. cochinchinensis* and most associated weed species, with the exception of *C. rotundus*. At the higher dose of 90+36 g/ha, slight phytotoxic symptoms were observed on maize shortly after application; however, the crop recovered completely within 10 days, indicating only transient injury. Isoxaflutole + thien carbazole–methyl

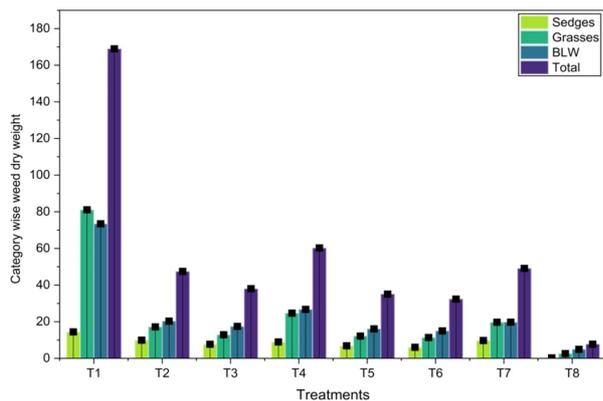


Figure 2. Effect of weed management treatments on weed biomass in maize at 56 DAHS

73.12+29.25 g/ha PE and EPoE was found effective in managing *Rottboellia cochinchinensis* and other weed species and it consistently achieved superior weed control efficiency, enhanced maize grain yield, and a reduced weed index relative to other herbicidal treatments, thereby confirming its effectiveness and crop safety under field conditions.

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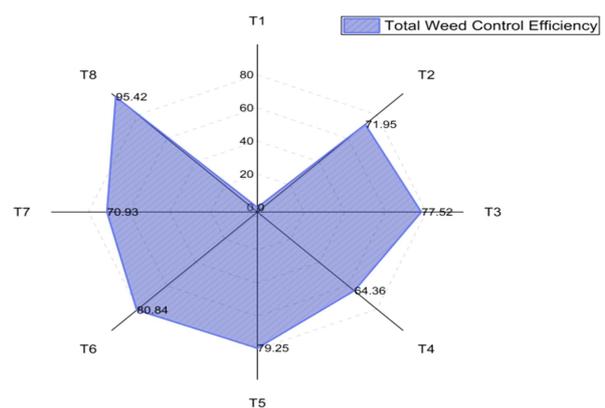


Figure 3. Effect of weed management treatments on WCE (%) in maize at 56 DAHS

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RESEARCH ARTICLE

Influence of weed management practices on weed dynamics, productivity and economics in summer greengram under different agroclimatic zones of Punjab, India

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ABSTRACT

A field experiment was conducted during three consecutive summer seasons (2022, 2023 and 2024) at different agroclimatic zones of Punjab, India, to study the effect of weed management practices on weeds and on summer greengram productivity and economics. A randomised block design comprising of 8 treatments with 4 replications was used. Hand weeding (HW) twice resulted in the lowest weed density and biomass, highest weed control efficiency (86.6% at 40 DAS and 84.0% at harvest) and highest greengram yield, which was statistically at par with post-emergence application (PoE) of imazethapyr 75 g/ha at 15 and 25 days after seeding (DAS). However, net return was higher with imazethapyr 75 g/ha PoE at 15 DAS and 25 DAS than HW twice. Imazethapyr 75 g/ha PoE at 15 DAS recorded the highest B:C (3.16). The residues of imazethapyr 50–75 g/ha PoE in grains at harvest were below the quantification limit (0.01 µg/g), confirming the safety of imazethapyr usage at recommended doses. It was concluded that effective and economical weed management in summer greengram, under different agroclimatic zones of Punjab, can be achieved, without any residual effects, with imazethapyr 75 g/ha PoE at 15 or 25 DAS.

Keywords: Greengram, Herbicide residues, Imazethapyr, Economics, Weed management

INTRODUCTION

Pulses are a rich source of protein (20–25%) and serve as a major source of dietary protein, especially because a large proportion of the Indian population is vegetarian. Among the grain legumes, greengram [*Vigna radiata* (L.) Wilczek], also known as mungbean is an important short-duration crop that can be grown year-round. One of the major constraints in greengram production is weed competition, which severely limits productivity (Mishra *et al.* 2016). Due to its slow initial growth, weeds establish rapidly during the early stages and compete vigorously with the crop for nutrients,

moisture, sunlight, and space, thereby causing considerable yield reduction. The loss of greengram yield due to weeds ranges from 58.2 to 76.2% (Barik *et al.* 2024, Hirani *et al.* 2024). Besides reducing crop yield, weeds also deteriorate crop quality, compete for nutrients, moisture, and light, and adversely affect soil nutrient status. Weed management plays a crucial role in the successful cultivation of summer greengram.

Traditionally, weed control by hand weeding is expensive and labour-intensive. However, weed control using herbicides was found to be a convenient, economical, and efficient (Verma and Kushwaha 2020). Hand weeding twice at 4 and 6 weeks after sowing (WAS) was recommended for effective weed control in summer greengram. However, often labour non availability for controlling weeds particularly at the critical period, is a major concern. Therefore, there was a need to find out effective weed management strategy. Herbicides were found to be very helpful in efficiently controlling weeds when labour is scarce (Virk *et al.* 2018). Hence, a field experiment was conducted to study the efficacy of imazethapyr at different doses and times

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of application to manage weeds in summer greengram under different agroclimatic zones of Punjab.

MATERIALS AND METHODS

The present study was carried out at the research farm of the Pulses Section, Department of Plant Breeding and Genetics, PAU Ludhiana (LDH) and Regional Research Stations (RRS) at Abohar (ABH), Faridkot (FDK) during summer season of 2022, 2023 and 2024, Gurdaspur (GSP) during summer 2023 and 2024, Bathinda (BTD) during summer 2022, Ballawal Saunkhri (BS) during summer 2024 to study the effect of imazethapyr on weeds and on greengram growth and grain yield. Eight treatments (**Table 1**) were tested in a randomized complete block design (RCBD with 4 replications, at all the locations. The tested treatments include: weedy check, hand weeding (HW) twice at 4 and 6 weeks after sowing (WAS), post-emergence application (PoE) of imazethapyr 50 g/ha at 15 days after sowing (DAS), imazethapyr 50 g/ha PoE at 25 DAS, imazethapyr 75 g/ha PoE at 15 DAS, imazethapyr 75 g/ha PoE at 25 DAS, pre-emergence application (PE) of imazethapyr 50 g/ha and imazethapyr 75 g/ha PE. PE herbicide was applied after sowing using 500 L of water per ha and PoE herbicide was applied using 375 L of water per ha according to the treatments at 15 or 25 DAS. The herbicides were applied by using knapsack sprayer fitted with a flood jet nozzle for PE application and flat fan nozzle for post-emergence application.

The greengram variety SML 1827 was sown at all the locations. The greengram was sown on 28 March 2022, 29 March 2023 and 27 March 2024 at Ludhiana, 6 April 2022, 10 April 2023 and 1 April 2024 at Abohar, 30 March 2023 and 26 March 2024 at Gurdaspur, 24 March 2024 at Ballawal Saunkhri, 25 March 2022, 11 April 2023 and 15 April, 2024 at Faridkot and 14 April 2022 at Bathinda. A seed rate of 30 kg/ha was used for sowing greengram in a row spacing of 22.5 cm. The greengram was raised as per the recommended package of practices. The crop was harvested on second to third week of June at all locations.

Weed density from each plot was recorded at 40 DAS with the help of quadrat. Dry weight of weeds (weed biomass) was recorded at 40 DAS and at harvest stages. For recording weed biomass, weed plants were removed from ground level by using quadrat of 50 cm × 50 cm, these samples were first sun dried and then dried in an oven to attain a constant weight. After drying, weed biomass was recorded

and expressed as g/m². Weed control efficiency (WCE) was calculated at 40 DAS and at harvest with the help of formula given below:

$$\text{WCE (\%)} = \frac{X - Y}{X} \times 100$$

Where

X = Weed biomass in weedy check

Y = Weed biomass in the treatment

At harvest, plant height, number of branches/plant and pods/plant were recorded by randomly selected five plants from each plot and average was worked out. Number of seeds per pod was recorded at harvest by counting the number of seeds of ten randomly selected pods and average was taken. A composite sample of seed from each net plot was drawn from the shelled pods and the 100 seeds were weighed separately for each net plot by electronic balance. After harvest of the crop, the biological yield/plot was recorded. Then after threshing of the harvested produce, grain yield/plot was recorded and grain yield was converted into t/ha. The economics of summer greengram was calculated based on prevailing market price. To calculate the net returns for each treatment, total cost of cultivation was subtracted from the gross returns. Benefit-cost ratio was calculated by dividing net returns with cost of cultivation.

A pooled analysis of location-wise data was performed. Data on weed density was subjected to square-root transformation before statistical analysis to normalize their distribution. Data were subjected to analysis of variance (ANOVA) in a randomized complete block design following standard procedures. All statistical comparisons among treatments were made at the 0.05 probability level ($P = 0.05$). Residues of imazethapyr in summer greengram at harvest were extracted as described by Sondhia *et al.* (2015) and quantified using Agilent HPLC coupled with a diode array detector (DAD) with λ_{max} of 225nm. Separation was performed on C-18 column (250×4.6mm) using Acetonitrile: 0.1% formic acid (80:20) as mobile phase at 0.8 mL min⁻¹ flow rate.

RESULTS AND DISCUSSION

Weed dynamics

Weed flora of experimental fields was predominated by annual dicot and monocot weeds. The major weeds in greengram at different locations include: *viz.*, *Digitaria sanguinalis*, *Cyperus rotundus* and *Trianthema portulacastrum* at Ludhiana, *Dactyloctenium aegyptium*, *Cyperus rotundus* and

Trianthema portulacastrum at Abohar, *Digera muricata* and *Cyperus rotundus* at Gurdaspur, *Cyperus rotundus*, *Cynodon dactylon* and *Sorghum halepense* at Ballawal Saunkhri, *Echinochloa crusgalli*, *Dactyloctenium aegyptium*, *Cyperus rotundus*, *Digera arvensis*, *Trianthema portulacastrum* at Faridkot and *Digera muricata*, *Cyperus rotundus* and *Trianthema portulacastrum* at Bathinda.

Significantly highest weed density and biomass (Table 1 and 2) was recorded in weedy check. Hand weeding twice at 4 and 6 weeks after sowing (WAS) recorded the lowest weed density at all locations (Table 1) as also observed by Kumar *et al.* (2019). The lowest weed density was also observed with imazethapyr 50 g/ha PoE at 15 and 25 DAS, imazethapyr 50 and 75 g/ha PE and was at par with imazethapyr 75 g/ha PoE at 15 and 25 DAS. The initial slow growth of weeds was due to herbicides which reduced the weed density, thereby minimizing competition and ensuring better crop–weed balance as reported by Meena *et al.* (2019) in pulses and by Kumar *et al.* (2020) in greengram.

Hand weeding twice recorded significantly lower weed biomass than the other treatments at 40 DAS at Ludhiana, Abohar and Gurdaspur. However, at Ballawal Saunkhri and Faridkot, HW twice recorded significantly lower weed biomass than weedy check, which was, however, at par with imazethapyr. At harvest, the lowest weed biomass was recorded with hand weeding twice at Ludhiana, which was statistically at par with imazethapyr 50 and 75 g/ha PE, while at Ballawal Saunkhri, the weed biomass with HW twice, imazethapyr 50 and 75 g/ha at 15 DAS, imazethapyr 50 and 75 g/ha PE, at Gurdaspur, HW twice and imazethapyr 75 g/ha at 15 DAS and at Abohar, two HW twice, imazethapyr 50 and 75 g/ha at 15 and 25 DAS were at par with each other. Most of the weeds were removed with HW

twice and only a few weeds emerged after 6 WAS and was statistically at par with imazethapyr 75 g/ha PoE at 15 and 25 DAS. This effectiveness could be attributed to the action of imazethapyr, which inhibits both root and shoot growth of weeds by inhibiting the enzyme acetolactate synthase (ALS). ALS is essential to produce branched-chain amino acids in plants; its inhibition leads to a disruption in protein synthesis, ultimately arrests plant growth and leading to weed mortality.

On an average, the lowest weed density was observed with HW twice, which was significantly lower than weedy check, imazethapyr 50 g/ha at 15 and 25 DAS, imazethapyr 50 and 75 g/ha as PE and at par with imazethapyr 75 g/ha at 15 and 25 DAS. Singh *et al.* (2014) also reported that imazethapyr at 75 and 100 g/ha at 25 DAS gave good control of weeds and the weed control efficiency was comparable to that of HW twice.

The highest weed control efficiency was recorded with HW twice (86.6 and 84.0%), which was significantly higher than other treatments, but it was statistically at par with imazethapyr 75 g/ha PoE at 15 DAS (80.4 and 76.5%) and imazethapyr 75 g/ha PoE at 25 DAS (82.0 and 75.7%) at 40 DAS and at harvest, respectively (Table 2). The comparable performance of imazethapyr with hand weeding suggests that the herbicide was effective in managing the major weeds during the critical crop–weed competition period as reported by Singh *et al.* (2018) and Yadav *et al.* (2017).

Effect on greengram

Greengram plant height was not significantly influenced by various weed management treatments at Abohar, Bathinda and Ballawal Saunkhri (Table 3). However, the highest plant height was recorded with HW twice, but it was statistically at par with imazethapyr 50 g/ha PoE at 15 and 25 DAS,

Table 1. Weed density as influenced by weed control treatments in summer greengram (pooled mean)

Treatment	Weed density (no./m ²)						
	LDH	ABH	GSP	BS	FDK	BTD	Mean
Weedy check	15.27 (117.0)	12.2 (151.7)	16.1 (51.2)	10.53 (40.0)	12.32 (151.7)	10.01 (101.0)	9.83 (102.1)
Hand weeding twice at 4 and 6 WAS	3.30 (4.7)	5.7 (35.3)	7.0 (8.3)	7.41 (18.0)	3.61 (12.3)	5.08 (26.0)	3.97 (17.4)
Imazethapyr 50 g/ha PoE at 15 DAS	7.33 (26.0)	8.8 (84.0)	11.1 (23.3)	6.00 (12.0)	5.49 (29.4)	6.32 (40.0)	5.71 (35.7)
Imazethapyr 50 g/ha PoE at 25 DAS	8.07 (28.7)	8.8 (81.7)	9.1 (14.8)	5.17 (7.4)	5.84 (33.2)	6.32 (40.0)	5.49 (34.2)
Imazethapyr 75 g/ha PoE at 15 DAS	7.53 (26.3)	7.7 (62.7)	10.4 (20.3)	5.43 (9.0)	3.80 (13.8)	5.90 (35.0)	5.03 (27.8)
Imazethapyr 75 g/ha PoE at 25 DAS	9.43 (41.0)	7.6 (58.7)	8.6 (13.3)	5.02 (7.0)	4.42 (18.8)	6.07 (37.0)	5.12 (29.3)
Imazethapyr 50 g/ha PE	6.20 (17.0)	9.8 (97.3)	13.2 (34.5)	6.79 (14.0)	7.38 (54.0)	6.43 (41.5)	6.23 (43.0)
Imazethapyr 75 g/ha PE	5.53 (13.7)	8.5 (73.7)	12.6 (31.0)	6.44 (12.0)	6.83 (46.2)	5.19 (27.0)	5.55 (33.9)
LSD (p=0.05)	2.7	1.8	1.7	0.8	0.8	0.9	1.3

Original data on weed density given in parentheses were subjected to square root transformation $\sqrt{x + 0.5}$ before analysis; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing
Abbreviation used: LDH: Ludhiana; ABH: Abohar; GSP: Gurdaspur; BS: Ballawal Saunkhri; FDK: Faridkot; BTD: Bathinda

imazethapyr 50 and 75 g/ha PE at Ludhiana, with imazethapyr 75 g/ha PoE at 15 and 25 DAS at Faridkot and Gurdaspur. On an average, HW twice recorded significantly higher plant height than weedy check, imazethapyr 50 g/ha at 15 DAS and 75 g/ha as PE and at par with other treatments of imazethapyr. The minimum plant height was recorded under weedy check plots at all locations, except at Ludhiana, where imazethapyr 75 g/ha PoE at 15 DAS recorded the lowest plant height. Application of imazethapyr at higher dose (75 g/ha) PoE at 15 DAS showed phytotoxic effects on crop, which resulted in reduction of plant height. Imazethapyr caused slight phytotoxicity in summer greengram, with an injury score of 8–9% on the 0–100% scale, from which the crop fully recovered within 15-20 days. The highest number of branches/plant was recorded with HW twice at 4 and 6 WAS at Abohar, Faridkot and

Gurdaspur, while, imazethapyr 50 g/ha PoE at 15 DAS, imazethapyr 75 g/ha PoE at 25 DAS and imazethapyr 75 g/ha PE recorded the highest number of branches/plant at Ludhiana, Bathinda and Ballawal Saunkhri, respectively (Table 3). The application of herbicides whether as pre-emergence or post-emergence and hand weeding effectively minimized weed interference, enabling better uptake of growth resources. As a result, the plants exhibited improved crop growth as reported by Rupareliya *et al.* (2017).

The highest number of pods/plant was recorded with HW twice at 4 and 6 WAS at all locations (Table 3). Among herbicidal treatments, imazethapyr 50 g/ha PoE at 15 DAS at Ludhiana, imazethapyr 75 g/ha PoE at 25 DAS at Abohar and Bathinda, imazethapyr 50 g/ha PoE at 25 DAS at Faridkot and imazethapyr 75 g/ha PoE at 15 DAS at Gurdaspur and Ballawal Saunkhri recorded the highest number of pods/plant

Table 2. Weed biomass and weed control efficiency as influenced by weed control treatments in summer greengram (pooled mean)

Treatment	LDH	ABH	GSP	BS	FDK	BTD	Mean	WCE (%)
<i>Weed biomass at 40 DAS (g/m²)</i>								
Weedy check	10.1 (50.5)	6.6 (53.3)	13.1 (169.7)	10.0 (101)	6.1 (41.6)	11.1 (124)	8.4 (84.6)	-
Hand weeding twice at 4 and 6 WAS	1.3 (1.0)	2.2 (5.0)	4.1 (17.3)	5.1 (26)	2.7 (7.1)	7.8 (61.2)	2.9 (11.3)	86.6
Imazethapyr 50 g/ha PoE at 15 DAS	3.7 (13.7)	4.4 (27.7)	5.7 (32.6)	6.3 (40)	3.6 (12.7)	4.9 (24.7)	4.3 (20.7)	75.5
Imazethapyr 50 g/ha PoE at 25 DAS	4.0 (15.8)	4.2 (25.3)	6.4 (41.0)	6.3 (40)	3.8 (14.6)	3.7 (13.7)	4.3 (20.6)	75.7
Imazethapyr 75 g/ha PoE at 15 DAS	3.7 (13.4)	3.7 (19.7)	4.4 (19.5)	5.9 (35)	3.6 (12.6)	4.6 (22.0)	3.9 (16.6)	80.4
Imazethapyr 75 g/ha PoE at 25 DAS	4.1 (16.6)	3.2 (13.3)	5.4 (21.8)	6.1 (37)	3.2 (9.9)	3.6 (13.2)	3.8 (15.2)	82.0
Imazethapyr 50 g/ha PE	3.3 (11.7)	5.1 (38.3)	7.8 (61.6)	6.4 (41)	2.6 (13.7)	6.0 (36.2)	4.7 (26.8)	68.3
Imazethapyr 75 g/ha PE	3.5 (13.1)	4.0 (23.3)	7.2 (52.4)	5.1 (27)	3.8 (14.4)	5.6 (32.2)	4.3 (21.2)	74.9
LSD (p=0.05)	0.7	0.9	0.9	3.3	2.1	3.1	1.1	7.2
<i>Weed biomass at harvest (kg/ha)</i>								
Weedy check	31.4 (1007)	25.3 (713)	42.7 (1727)	9.6 (93)	23.7 (571)		31.3 (1108)	-
Hand weeding twice at 4 and 6 WAS	7.7 (105)	15.1 (237)	16.4 (221)	4.7 (22)	10.9 (200)		12.3 (178)	84.0
Imazethapyr 50 g/ha PoE at 15 DAS	15.0 (229)	19.8 (517)	23.1 (486)	5.6 (31.7)	17.7 (314)		17.5 (364)	67.2
Imazethapyr 50 g/ha PoE at 25 DAS	18.7 (356)	18.8 (500)	24 (536)	6.4 (41)	16.9 (283)		18.1 (390)	64.8
Imazethapyr 75 g/ha PoE at 15 DAS	13.9 (198)	17.1 (373)	16.8 (237)	5.4 (30)	17.0 (291)		14.9 (260)	76.5
Imazethapyr 75 g/ha PoE at 25 DAS	15.7 (256)	14.6 (280)	20.1 (355)	6.3 (40)	17.2 (296)		15.4 (269)	75.7
Imazethapyr 50 g/ha PE	11.6 (156)	23.5 (673)	28.8 (784)	4.9 (24)	17.4 (312)		19.1 (455)	58.9
Imazethapyr 75 g/ha PE	10.3 (120)	20.0 (477)	26.8 (682)	4.8 (23)	17.0 (307)		17.4 (367)	66.9
LSD (p=0.05)	4.3	5.2	3.4	1.5	4.2		3.6	10.1

Original data on weed density given in parentheses were subjected to square root transformation $\sqrt{x + 0.5}$ before analysis; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing
Abbreviation used: LDH: Ludhiana; ABH: Abohar; GSP: Gurdaspur; BS: Ballawal Saunkhri; FDK: Faridkot; BTD: Bathinda

Table 3. Plant height, branches/plant and pods/plant of summer greengram as influenced by weed control treatments (pooled mean)

Treatment	Plant height (cm)						Branches/plant						Pods/plant					
	LDH	ABH	GSP	BS	FDK	BTD	LDH	ABH	GSP	BS	FDK	BTD	LDH	ABH	GSP	BS	FDK	BTD
Weedy check	59.5	48.7	57.3	29.3	47.8	66.3	5.99	4.34	7.24	4.31	4.11	4.08	20.6	13.6	14.6	15.0	21.3	13.5
Hand weeding twice at 4 and 6 WAS	62.9	54.5	64.2	30.8	57.7	69.6	6.17	5.84	11.69	5.40	6.06	5.30	25.3	25.2	20.3	18.6	29.7	20.8
Imazethapyr 50 g/ha PoE at 15 DAS	61.7	50.9	62.0	30.2	55.3	68.0	6.61	4.96	10.24	4.72	4.94	5.15	26.0	21.1	19.3	17.9	28.2	17.8
Imazethapyr 50 g/ha PoE at 25 DAS	61.1	51.7	61.9	33.4	54.8	69.7	6.34	5.20	10.09	4.40	4.91	5.38	22.7	22.1	19.7	17.7	29.0	19.5
Imazethapyr 75 g/ha PoE at 15 DAS	58.9	52.6	63.4	32.8	55.6	69.8	6.16	5.40	11.15	5.10	5.04	5.34	24.4	23.1	20.3	18.5	27.0	19.3
Imazethapyr 75 g/ha PoE at 25 DAS	59.3	53.2	63.4	33.7	55.5	70.0	6.40	5.58	10.85	4.82	5.44	5.45	21.6	24.4	19.7	18.2	28.8	20.3
Imazethapyr 50 g/ha PE	61.1	50.3	60.4	34.8	54.8	69.3	6.28	5.07	9.79	5.10	5.28	5.13	22.6	18.2	19.9	18.0	27.4	17.5
Imazethapyr 75 g/ha PE	61.3	49.6	60.1	31.4	54.8	69.5	6.22	4.46	9.34	5.45	5.01	5.20	23.2	15.4	20.0	18.0	25.7	18.0
LSD (p=0.05)	3.1	NS	1.9	NS	2.4	NS	0.70	0.56	1.40	NS	0.78	0.64	1.8	4.3	2.3	NS	4.3	2.2

Abbreviation used: LDH: Ludhiana; ABH: Abohar; GSP: Gurdaspur; BS: Ballawal Saunkhri; FDK: Faridkot; BTD: Bathinda; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing

in greengram. Number of seeds/pod was not significantly affected by different weed management practices at Ludhiana, Abohar, Gurdaspur and Ballowal Saunkhri (Table 4). However, imazethapyr 75 g/ha PoE at 15 DAS at Faridkot and imazethapyr 75 g/ha PoE at 25 DAS at Bathinda recorded the maximum number of seeds/pod in greengram. Imazethapyr 50 g/ha PoE at 15 DAS at Ludhiana, imazethapyr 50 g/ha PoE at 25 DAS at Abohar, imazethapyr 75 g/ha PoE at 15 DAS at Faridkot and Gurdaspur, imazethapyr 75 g/ha PoE at 25 DAS at Bathinda and imazethapyr 50 g/ha PE recorded the highest seed index of greengram (Table 4).

The highest grain yield of greengram was recorded with HW twice at 4 and 6 WAS at all locations, except Bathinda, where, imazethapyr 75 g/ha PoE at 25 DAS gave the highest grain yield (Table 5). At Ludhiana, application of imazethapyr 50 and 75 g/ha PoE at 15 DAS, at Abohar imazethapyr 75 g/ha PoE at 25 DAS, and at Ballowal Saunkhri imazethapyr 75 g/ha PE produced grain yields statistically at par with HW twice. Similarly, at Gurdaspur, Faridkot, and Bathinda, the herbicidal treatments were on par with two HW. On an average, HW twice at 4 and 6

WAS, imazethapyr 75 g/ha PoE at 15 and 25 DAS recorded statistically similar grain yield of greengram and significantly higher than the other treatments. HW twice, imazethapyr 75 g/ha PoE at 15 and 25 DAS enhanced grain yield of greengram by 71.4, 60.2 and 58.5% over weedy check, respectively. Punia *et al.* (2017) also reported significant yield enhancement in greengram with the application of imazethapyr 70 g/ha applied at 3-4 leaf stage. The superior yield performance with HW twice and herbicidal treatments can be attributed to their effective weed control (Tables 1 and 2), thereby improving light interception, nutrient uptake, and moisture availability for the crop (Singh *et al.* 2018).

Economics

The HW twice at 4 and 6 WAS recorded maximum gross return, which were significantly higher than weedy check and other treatments, but at par with imazethapyr 75 g/ha PoE at 15 and 25 DAS (Table 5). Imazethapyr 75 g/ha PoE at 15 DAS recorded the highest net return followed by imazethapyr 75 g/ha at 25 DAS. The slightly lower net return with under HW twice was due to the higher

Table 4. Number of seeds/pod and seed index of summer greengram as influenced by weed control treatments (pooled mean)

Treatment	Seeds/pod						Mean	Seed index (g)						Mean
	LDH	ABH	GSP	BS	FDK	BTD		LDH	ABH	GSP	BS	FDK	BTD	
Weedy check	11.5	10.5	10.4	10.1	7.00	8.3	9.6	3.93	3.89	3.14	3.55	3.74	3.03	3.65
Hand weeding twice at 4 and 6 WAS	11.9	11.8	11.2	11.8	8.85	11.0	10.8	3.93	3.97	4.04	4.06	4.05	3.05	3.92
Imazethapyr 50 g/ha PoE at 15 DAS	11.8	11.2	11.0	11.4	9.05	10.0	10.5	4.12	3.92	3.87	3.97	4.12	3.13	3.93
Imazethapyr 50 g/ha PoE at 25 DAS	11.9	11.3	10.9	11.1	8.65	11.0	10.5	4.08	4.05	3.83	3.96	4.10	3.2	3.95
Imazethapyr 75 g/ha PoE at 15 DAS	12.0	11.5	11.2	11.5	9.08	10.3	10.6	4.09	3.88	4.07	3.96	4.21	3.23	3.97
Imazethapyr 75 g/ha PoE at 25 DAS	11.9	11.7	11.2	11.5	8.60	11.1	10.6	4.01	4.02	3.94	4.01	4.13	3.25	3.96
Imazethapyr 50 g/ha PE	12.0	10.8	10.8	10.8	8.85	10.5	10.4	4.02	3.80	3.80	4.19	4.07	3.13	3.88
Imazethapyr 75 g/ha PE	11.7	10.7	10.8	10.9	8.60	10.3	10.3	4.09	3.75	3.83	3.99	3.95	3.15	3.85
LSD (p=0.05)	NS	NS	NS	NS	0.42	1.3	0.3	0.20	0.26	0.24	NS	0.19	NS	0.12

Abbreviation used: LDH: Ludhiana; ABH: Abohar; GSP: Gurdaspur; BS: Ballowal Saunkhri; FDK: Faridkot; BTD: Bathinda; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing

Table 5. Effect of weed management treatments on grain yield and economics of summer greengram (pooled mean)

Treatment	Greengram grain yield (t/ha)							Cost of cultivation (Rs/ha)	Gross returns (Rs/ha)	Net returns (Rs/ha)	B:C ratio
	LDH	ABH	GSP	BS	FDK	BTD	Mean				
Weedy check	1.44	0.94	0.99	0.56	1.01	0.20	0.86	29038	86299	57261	1.97
Hand weeding twice at 4 and 6 WAS	1.94	1.67	1.57	1.13	1.50	1.01	1.47	49038	137783	88745	1.81
Imazethapyr 50 g/ha PoE at 15 DAS	1.89	1.32	1.39	0.84	1.43	0.94	1.30	29733	123371	93638	3.15
Imazethapyr 50 g/ha PoE at 25 DAS	1.73	1.43	1.38	0.69	1.40	0.95	1.26	29733	120940	91207	3.07
Imazethapyr 75 g/ha PoE at 15 DAS	1.90	1.42	1.54	0.93	1.39	1.06	1.37	30880	128407	97527	3.16
Imazethapyr 75 g/ha PoE at 25 DAS	1.72	1.57	1.54	0.76	1.41	1.16	1.36	30880	127625	96745	3.13
Imazethapyr 50 g/ha PE	1.75	1.24	1.28	1.05	1.33	0.79	1.24	30533	115905	85372	2.80
Imazethapyr 75 g/ha PE	1.79	1.09	1.28	1.10	1.29	0.82	1.23	30880	113647	82767	2.68
LSD (p=0.05)								-	12220	12220	0.18

Abbreviation used: LDH: Ludhiana; ABH: Abohar; GSP: Gurdaspur; BS: Ballowal Saunkhri; FDK: Faridkot; BTD: Bathinda; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing

Table 6. Residue of imazethapyr in grains of greengram at harvest after its usage for weed management in summer greengram

Treatment	Residue in summer greengram ($\mu\text{g/g}$)
Imazethapyr 50 g/ha PoE at 15 DAS	<LOQ
Imazethapyr 50 g/ha PoE at 25 DAS	<LOQ
Imazethapyr 100 g/ha PoE at 25 DAS	0.018 ± 0.011
Imazethapyr 75 g/ha PoE at 15 DAS	<LOQ
Imazethapyr 75 g/ha PoE at 25 DAS	<LOQ
Imazethapyr 150 g/ha PoE at 25 DAS	0.049 ± 0.012
Imazethapyr 50 g/ha PE	<LOQ
Imazethapyr 75 g/ha PE	<LOQ
Imazethapyr 150 g/ha PE	0.027 ± 0.018

LOQ (Limit of Quantification) $<0.01 \mu\text{g/g}$; PoE: post-emergence application; PE: pre-emergence application DAS: days after sowing; WAS: weeks after sowing

labour costs involved, despite higher gross returns. Imazethapyr 75 g/ha PoE at 15 DAS gave the highest BC ratio (3.16) followed by imazethapyr 50 g/ha PoE at 15 DAS (3.15) and imazethapyr 75 g/ha PoE at 25 DAS (3.13) as reported by Singh *et al.* 2018 and Punia *et al.* 2017).

Herbicide residue in grains

The calibration curves of imazethapyr were linear with correlation coefficient $R^2 > 0.99$. Limit of detection (LOD) and limit of quantification (LOQ) of imazethapyr were 0.003 and $0.01 \mu\text{g/g}$, respectively. The mean percent recoveries from greengram at fortification levels of 0.5, 0.1 and $0.01 \mu\text{g/g}$ ranged from 82.5 ± 2.21 to 94.3 ± 2.78 . Inter day precision (percent RSD_R) and intraday precision (percent RSD_I) was assessed by repeating experiment three times a day and on three different days, respectively and were <10 percent. The harvest residues of imazethapyr in greengram when applied at 75 g/ha after 15 and 25 DAS, were below $0.01 \mu\text{g g}^{-1}$. When imazethapyr was applied at 100 and 150 g/ha 25 DAS and at 150 g/ha as PE, residues corresponding to 0.018 ± 0.011 , 0.049 ± 0.012 and $0.027 \pm 0.018 \mu\text{g/g}$, respectively were detected in greengram (Table 6). These results indicate that lower recommended doses of imazethapyr (50–75 g/ha) are safe for application in greengram, as the residues were below the limit of quantification (LOQ) as observed earlier by Punia *et al.* (2017) in greengram.

Conclusion

Imazethapyr 75 g/ha PoE at 15 and 25 DAS was found to be the most effective and economic approach for weed management to realise higher greengram productivity of summer greengram under different agro climatic zones of Punjab, India.

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RESEARCH ARTICLE

Dissipation of metribuzin, pendimethalin and clodinafop-propargyl, applied in pea, as influenced by mulching and climatic variables

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ABSTRACT

Pea (*Pisum sativum* L.) is a major legume valued for its high protein content and nitrogen fixation, but persistence of herbicides like pendimethalin, metribuzin and clodinafop-propargyl raises concerns of food safety and their carryover effect on succeeding crops. A field study was conducted to evaluate dissipation kinetics of pre-emergence application (PE) of pendimethalin 750 g/ha and post-emergence application (PoE) of clodinafop-propargyl + metribuzin 169, 202, 236 and 270 g/ha in pea crop with the paddy straw mulch of 7.5 t/ha, under varying climatic conditions that prevailed in different years of evaluation. Clodinafop-propargyl remained below 0.01 µg/g due to rapid hydrolysis into clodinafop acid. The half-lives of pendimethalin and metribuzin varied markedly across years, with faster dissipation in the 2024–25, year with higher early-season rainfall, and slower degradation in the 2022–23 and 2023–24, years with limited rainfall. Mulching increased pendimethalin persistence by moderating soil temperature and moisture, and reducing volatilization and photodegradation whereas clodinafop-propargyl + metribuzin dissipated rapidly when applied over mulch due to greater exposure to sunlight and air. At harvest, residues of all herbicides were below the limit of detection (<0.01 µg/g) in soil and pea across all study years, indicating that at recommended application rates these herbicides dissipate efficiently without leaving harmful residues, thereby ensuring food safety.

Keywords: Pendimethalin, Metribuzin, Clodinafop-propargyl, Crop safety assessment, Herbicide residues

INTRODUCTION

Weeds represent one of the most persistent biotic constraints in modern agriculture, severely impacting crop growth, yield and quality by competing for light, water, nutrients and space (Rao *et al.* 2020). In response to these challenges, herbicides have become an essential component of integrated weed management strategies due to their efficacy, convenience and ability to control a wide spectrum of weed species with minimal labour input (Rao 2022). The widespread adoption of herbicides has contributed significantly to the intensification of agricultural systems, enabling high crop productivity and enhanced food security (Abraham *et al.* 2014, Rao 2022). However, the extensive and often indiscriminate use of herbicides has also raised critical environmental and health concerns, particularly with respect to their persistence in soil, potential leaching into groundwater and accumulation in edible crops (Sondhia *et al.* 2019).

Pisum sativum (pea), an agronomically and nutritionally important legume, plays a vital role in

sustainable agriculture by contributing to soil nitrogen enrichment through symbiotic nitrogen fixation, improving soil structure and providing rotational diversity in cropping systems (Akshith *et al.* 2024). Pendimethalin and metribuzin + clodinafop-propargyl have been widely recognized for their efficacy in controlling annual weeds in leguminous and other pea crops, providing a valuable tool for modern weed management (Chikoye *et al.* 2014). Pendimethalin, a dinitroaniline herbicide, is commonly used for pre-emergence weed control and exerts its action by inhibiting microtubule polymerization during cell division (Giglio and Vommaro 2022). Metribuzin is a selective triazinone herbicide primarily targeting broad-leaved and some grass weeds. It inhibits photosystem II by attaching to the D1 protein of chloroplast thylakoid membrane, thereby interrupting electron transport and halting photosynthesis (Teixeira *et al.* 2024). Clodinafop-propargyl, a post-emergence herbicide, selectively controls grassy weeds by inhibiting acetyl-CoA carboxylase (ACCase), an enzyme critical for fatty acid biosynthesis in susceptible species (Zand and Foroushani 2015, EFSA 2015). However, the continued persistence of these herbicides in agricultural soils is a critical concern, directly

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impacting crop rotation and the potential for carryover damage to subsequent crops. Accurate and timely monitoring of their dissipation is essential not only to ensure food safety and compliance with maximum residue limit (MRL) standards but also to protect soil fertility, maintain beneficial microbial populations and safeguard the long-term sustainability of agricultural ecosystems.

Despite their widespread use, there is notable scarcity of published research dealing with dissipation kinetics and terminal residues of pendimethalin, metribuzin and clodinafop-propargyl when applied to pea crop (Sondhia 2013) specifically in sub-tropical climatic conditions of Punjab. Considering the widespread reliance on herbicides for pea production, the present study was undertaken over three consecutive years (2022-23, 2023-24 and 2024-25) with the objective of evaluating the dissipation kinetics and terminal residues of pendimethalin, metribuzin and clodinafop-propargyl applied in pea for the assessment of residue risk and to provide a scientific basis for safe herbicide usage in pea-based production systems.

MATERIALS AND METHODS

Chemicals and sample preparation

Analytical standards of metribuzin (purity 98%), pendimethalin (purity 98%) and clodinafop-propargyl (purity 97.8%) was procured from TCI Chemicals, Tokyo, Japan. Solvents of HPLC and analytical grade were supplied by Qualikems Pvt, Ltd., Mumbai, India. A stock solution of each herbicide (1000 µg/mL) was prepared in HPLC-grade acetonitrile and working standard solutions ranging from 0.01 to 10 µg/mL were prepared through serial dilution of the stock solution. Commercial formulations, Shagun 21 11 (ready-mix of clodinafop-propargyl 12% plus metribuzin 42% WG) [hereafter: clodinafop-propargyl + metribuzin (ready-mix)] and Stomp (pendimethalin 30 EC) (hereafter: pendimethalin), were procured from the local market of Ludhiana, Punjab, India.

Degradation studies

Field experiments were conducted at the Agronomy Research Farm, Punjab Agricultural University, Ludhiana, during the *Rabi* seasons of 2022-23, 2023-24, and 2024-25 to evaluate the degradation behavior of herbicides in pea under different weed management practices. The soil of the experimental site was loamy sand and the experiment was laid out in a randomized complete block design (RCBD) with three replications. Each plot measured 4

m × 2.5 m. Pea variety 'Punjab 89' was sown on November 2, 2022; October 31, 2023 and November 5, 2024, at a spacing of 30 cm × 10 cm using a seed rate of 75 kg/ha. The seed was inoculated with *Rhizobium legumin Sarum* culture at 625 g/ha prior to sowing. Basal fertilization consisted of 50 kg/ha nitrogen (through 112.5 kg/ha urea) and 62.5 kg/ha phosphorus (through 387.5 kg/ha single superphosphate). In mulching treatments, paddy straw mulch was applied at 7.5 t/ha uniformly over the soil surface three days after sowing. The pre-emergence application (PE) of pendimethalin 750 g/ha was done one day after sowing (before mulch placement) on 03 November 2022, 01 November 2023 and 06 November 2024 using a calibrated knapsack sprayer fitted with a flat-fan nozzle at 500 L/ha spray volume. The post-emergence application (PoE) of clodinafop-propargyl + metribuzin (ready-mix) was applied 30 to 35 days after sowing (DAS) (05 December 2022, 05 December 2023 and 08 December 2024) at 169, 202, 236 and 270 g/ha. The inclusion of herbicide treatments in mulched plots was intended to study the interactive effects of chemical and physical weed suppression and to evaluate the degradation behaviour of metribuzin under conditions of reduced soil exposure and sunlight interception. Although mulching alone suppresses 60-70% of the weed flora, certain species still emerge through small gaps or along mulch edges; therefore, integrating herbicides with mulch represents a practical approach for more effective and prolonged weed control. This also allowed an assessment of influences of mulching on dissipation of herbicide. At the applied mulch rate, there was no adverse effect of mulching on pea emergence and growth. Meteorological data during the crop growth period is given in **Figure 1**. For herbicide dissipation and residue monitoring, soil samples (0-15 cm) were collected at 0 (4 hours after application), 3, 5, 7, 10, 15, 21, 30, 45, 60 and 90 days after herbicide application (DAA) and at harvest. Each composite sample represented 6-7 cores from random locations in each plot. Pea samples were collected at three successive pickings to monitor residue dynamics during the harvest period. Samples were stored at -4°C and analyzed within one week. Residue data from mulched and non-mulched plots were analyzed separately and dissipation kinetics curves were generated to depict metribuzin degradation patterns under different surface conditions.

Extraction methods

Matrix solid phase dispersion (MSPD) method was used for the extraction of herbicides from soil

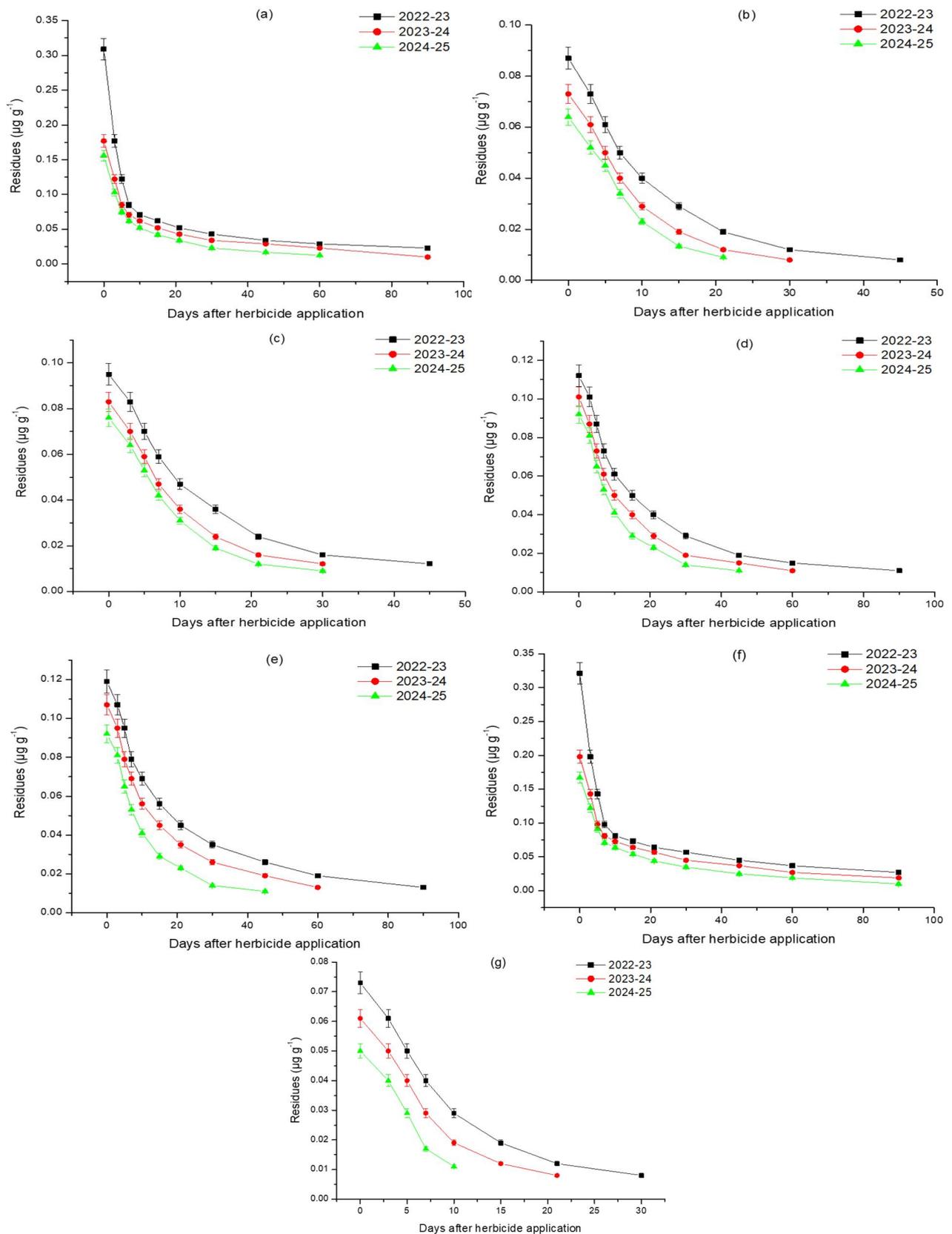


Figure 2. Dissipation curves of pendimethalin in (a) Pendimethalin 750 g/ha and metribuzin in (b) Clodinafop + metribuzin 169 g/ha (c) Clodinafop + metribuzin 202 g/ha (d) Clodinafop + metribuzin 236 g/ha (e) Clodinafop + metribuzin 270 g/ha; pendimethalin in (f) Pendimethalin 750 g/ha followed by paddy straw mulch 7.5 t/ha and metribuzin in (g) Paddy straw mulch 7.5 t/ha followed by clodinafop + metribuzin 169 g/ha in different years

and pea. Briefly, 10 g of soil/pea sample was blended thoroughly with 5 g of pre-activated florisol using pestle and mortar to ensure uniform dispersion. The activation of florisol was performed at 200°C for 8 hours prior to use. The homogenized mixture was then packed into clean glass column pre-layered with 3 g of activated charcoal and 2 g of anhydrous sodium sulfate. The column was eluted with 50 mL of acetone for pendimethalin and 60 mL for metribuzin and 50 mL of ethyl acetate for clodinafop-propargyl. The collected eluate was concentrated to dryness using a rotary vacuum evaporator and residues were redissolved in 2 mL of acetonitrile prior to chromatographic analysis.

Quantification of herbicides

The residue analysis was carried out using HPLC-Waters equipped with 2489 UV-visible detector. Herbicide separation was achieved using C18 spherisorb column (5.0 µm ODS2, 4.6 mm × 250 mm) at 297 nm for metribuzin and 240 nm for pendimethalin and clodinafop. The mobile phase consisted of acetonitrile: water (8:2, v/v) at a flow rate of 0.8 mL/min. The retention time of metribuzin, pendimethalin and clodinafop was 2.84, 4.29 and 7.70 minutes, respectively.

Method validation

The analytical method was validated by evaluating matrix effect, limit of detection (LOD), limit of quantification (LOQ), accuracy and precision (SANTE 2020). Matrix effect (ME) was calculated as: $ME(\%) = \left[\frac{\text{slope of calibration curve for analyte in organic solvent (SSC)}}{\text{slope of calibration curve for analyte in matrix (MMC)}} - 1 \right] \times 100$ where, SSC is solvent calibration curve prepared in acetonitrile and MMC corresponds to the calibration curve obtained by spiking blank matrix samples. LOD and LOQ were established at the signal to noise ratios of 3:1 and 10:1, respectively. Accuracy was evaluated

by analysing samples fortified at two concentration levels: 0.05 and 0.01 µg/mL. To assess intraday precision (%RSD_t), the experiment was performed three times within a single day, while interday precision (%RSD_R) was determined by conducting the analysis on three different days, each with three replicate measurements at 0.05 and 0.01 µg/mL.

Data analysis

Dissipation kinetics of herbicides were estimated using first order model expressed as: $\ln C_t = \ln C_0 - kt$, where C_0 is initial and C_t is the concentration at time t (days) in µg/g and k (day⁻¹) is the degradation rate constant. Half-life (DT₅₀) was calculated using the equation: $DT_{50} = \ln 2/k$. Statistical analyses were performed using SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Analysis of variance (ANOVA) was applied to assess significant differences among treatments.

RESULTS AND DISCUSSION

Validation studies

The matrix effect was found to be below 5%, confirming method's selectivity and reliability for the estimation of metribuzin, pendimethalin and clodinafop-propargyl in soil and pea samples (Table 1). The LOD and LOQ was 0.003 and 0.01 µg/g demonstrating good sensitivity, enabling the precise detection and quantification of studied herbicides in studied matrices. The mean percent recoveries from soil and pea at fortification levels ranging from 0.01 to 0.05 µg/g varied from 89.9 ± 2.99 to 95.4 ± 2.19 and 82.1 ± 2.01 to 89.3 ± 3.56, respectively (Table 1) with %RSD_r and %RSD_R <10% confirming that the method was accurate and precise for extracting pendimethalin, metribuzin and clodinafop-propargyl from soil and pea.

Table 1. Mean percent recoveries, inter and intra-day precision and matrix effect of studied herbicides from soil and pea

Parameters	Herbicide	Soil		Pea	
		0.05	0.01	0.05	0.01
Recovery %	Metribuzin	95.4 ± 2.19	91.0 ± 3.23	88.3 ± 2.76	84.3 ± 2.67
	Pendimethalin	92.3 ± 1.67	90.2 ± 2.18	89.3 ± 3.56	83.2 ± 2.99
	Clodinafop-propargyl	91.2 ± 2.10	89.9 ± 2.99	85.4 ± 3.51	82.1 ± 2.01
RSD _t	Metribuzin	2.63	1.61	3.21	2.51
	Pendimethalin	3.22	2.92	3.12	3.11
	Clodinafop-propargyl	2.61	3.11	2.01	3.93
RSD _R	Metribuzin	3.23	2.33	3.23	2.32
	Pendimethalin	1.71	3.21	1.53	3.23
	Clodinafop-propargyl	2.00	2.72	2.61	1.93
Matrix effect	Metribuzin		2.3		3.6
	Pendimethalin		3.8		4.1
	Clodinafop-propargyl		4.5		2.9

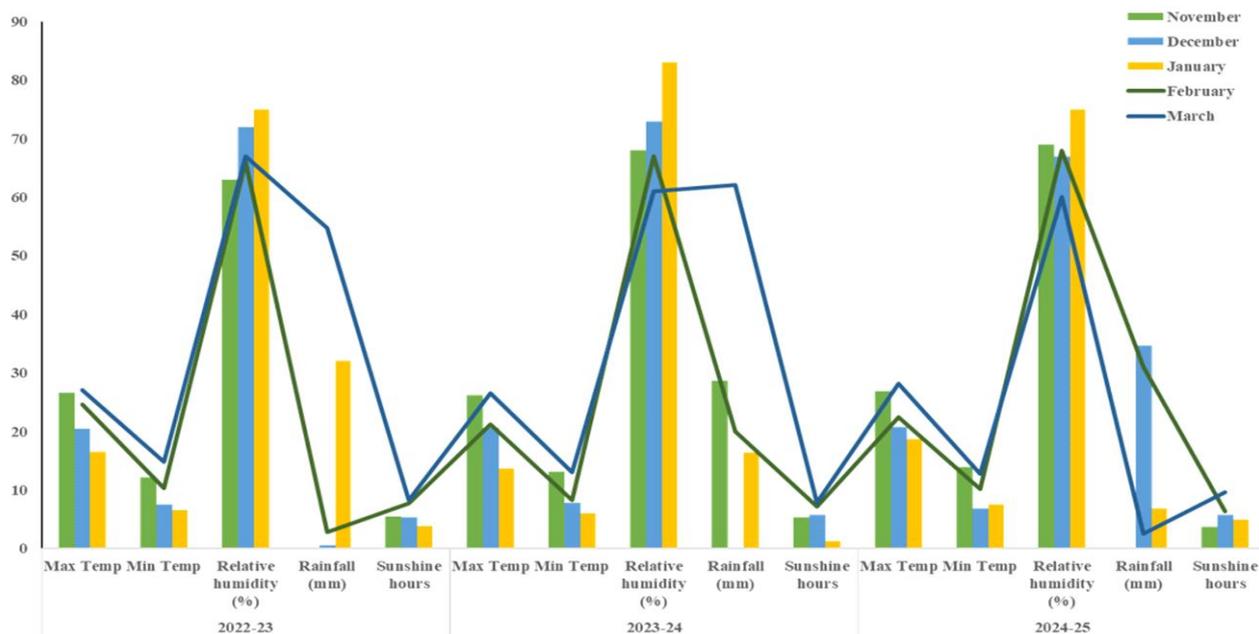


Figure 1. Weather data recorded during the experimental period (Source: Department of Climate Change and Agricultural Meteorology, PAU, Ludhiana)

Degradation studies

The initial residue of clodinafop-propargyl over three-year study was <0.01 µg/g probably due to its rapid hydrolysis into clodinafop acid. (Chhokar *et al.* 2009; Wang *et al.* 2018; Kaur *et al.* 2023). During the study period the initial residual concentrations of pendimethalin and metribuzin varied between 0.156 ± 0.012 to 0.321 ± 0.023 and 0.05 ± 0.015 to 0.119 ± 0.019 µg/g respectively (Figure 2). The residues of pendimethalin and metribuzin declined considerably over time. The dissipation behaviour of studied herbicides followed first order kinetics with determination coefficients (R²) > 0.99. ANOVA results indicated a significant interaction (p<0.05) between herbicide application rates and the prevailing environmental conditions. The half-lives (DT₅₀) for the different herbicide treatments are presented in Table 2. Across all three years, pendimethalin demonstrated a significantly higher persistence in the soil compared to all metribuzin-containing treatments.

The DT₅₀ of pendimethalin applied alone (750 g/ha) ranged from 24.46 to 38.86 days, while the DT₅₀ for the various clodinafop + metribuzin treatments were substantially lower, ranging from 4.32 to 25.56 days. This finding indicates that pendimethalin has a slower degradation rate and a higher potential for residual accumulation in the soil environment compared to metribuzin.

A clear trend of decreasing herbicide persistence was observed over the three years of the study. The half-lives of pendimethalin and metribuzin ranged from 12.47 to 38.86, 8.89 to 32.77 and 6.94 to 24.46 days in 2022-23, 2023-24, 2024-25, respectively, indicating faster degradation of pendimethalin in 2024-25 compared to 2023-24 and 2022-23 (Table 2). This pattern reflects the influence of year-to-year climatic variation among the three growing seasons. Among the climatic factors, rainfall showed the most pronounced variation and was therefore the primary driver of differences in dissipation rates. The year

Table 2. Half-lives (days) of pendimethalin and metribuzin in different treatments in different years

Treatment	Half-lives (days)		
	2022-23	2023-24	2024-25
Pendimethalin 750 g/ha	38.86	32.77	24.46
Pendimethalin 750 g/ha followed by paddy straw mulch 7.5 t/ha	50.65	41.02	30.57
Paddy straw mulch 7.5 t/ha followed by clodinafop + metribuzin 169 g/ha	8.89	6.72	4.32
Clodinafop + metribuzin 169 g/ha	12.47	8.89	6.94
Clodinafop + metribuzin 202 g/ha	14.19	10.10	8.99
Clodinafop + metribuzin 236 g/ha	18.76	16.46	13.86
Clodinafop + metribuzin 270 g/ha	25.56	19.86	17.97

2024-25 received substantially higher early-season rainfall (34.6 mm), which likely increased soil moisture and stimulated microbial activity, conditions known to accelerate the degradation of soil-applied herbicides and resulted in shorter half-lives. In contrast, in the year 2022-23 was extremely dry with almost no rainfall (0.6 mm), leading to reduced soil moisture and less favourable conditions for microbial or hydrolytic breakdown, thereby prolonging herbicide persistence. The year 2023-24 season experienced intermediate rainfall, producing dissipation rates between the other two years. Although the experiments were conducted in the same field, accelerated dissipation due to microbial adaptation is unlikely because different herbicides were applied in the intervening maize crop each year. The absence of continuous exposure to the same herbicide prevented the sustained selection pressure required for microbial enrichment (Kaur *et al.* 2016, Kaur *et al.* 2017a, Kaur *et al.* 2017b).

The application of paddy straw mulch had a notable effect on the dissipation of pendimethalin. Treatments that included paddy straw mulch showed consistently higher DT₅₀ values (30.57 to 50.65 days) compared to the treatments where pendimethalin was applied alone (24.46 to 38.86 days). This indicates that the presence of paddy straw mulch likely slowed the degradation of pendimethalin, thereby increasing its persistence in the soil. This effect could be attributed to the mulch layer moderating soil temperature and moisture levels or providing a physical barrier that reduces volatilization and photodegradation of pendimethalin. In contrast, the treatment involving paddy straw mulch followed by clodinafop + metribuzin resulted in the lowest DT₅₀ values observed across all treatments, with a range of 4.32 to 8.89 days. This rapid dissipation is likely due to the herbicide being applied on top of the mulch layer. The straw provides a large surface area for the herbicide to come in contact with sunlight and air, potentially leading to faster photodegradation and volatilization before it can even reach the soil (Douibi *et al.* 2024, Chen *et al.* 2025). This suggests that the timing and placement of the herbicide relative to the mulch application are critical factors influencing dissipation.

The residues of pendimethalin, metribuzin and clodinafop-propargyl in soil at pea harvest were below the limit of detection (<0.01 µg/g) across all study years. This observation confirms that, under all the treatments these herbicides do not persist in the environment at levels that pose a risk to either the

subsequent crops or the broader agroecosystem. In pea, residues of pendimethalin, metribuzin, and clodinafop-propargyl were below detection limit of <0.01 µg/g at each harvest stage (first, second, and third picking). Residue below the maximum residue limit (MRL) of 0.1 mg/g in pea samples at harvest demonstrates minimal risk of pendimethalin and pre-mix of clodinafop-propargyl + metribuzin (USEPA 1998; EFSA 2015; EFSA 2023), thereby confirming compliance with food safety regulations. Nevertheless, continuous monitoring and strict adherence to recommended guidelines remain essential to safeguard consumer safety and ensure the sustained quality of pea production.

Conclusion

The present study demonstrated that pendimethalin dissipates more slowly than metribuzin, highlighting its higher persistence in soil and greater potential for residual accumulation. Variability in degradation patterns was strongly influenced by mulching and environmental factors, with higher rainfall accelerating dissipation rates as in 2024-25 compared to lower rain fall years of 2023-24 and 2022-2023. Residues of metribuzin, pendimethalin and clodinafop-propargyl in soil and pea samples remained below detectable limits and below established maximum residue limits, confirming their safety when used at recommended application rates.

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RESEARCH ARTICLE

Efficacy of pre-emergence application of diclosulam on weeds and crop productivity of soybean-mustard cropping system

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ABSTRACT

An experiment was conducted during *Kharif* seasons of 2020 and 2021 to test the bio-efficacy of diclosulam 84% WDG (diclosulam) for weed management in *Kharif* season soybean and its succeeding effect on mustard in *Rabi* season. The study was conducted at District Seed farm-C unit, Bidhan Chandra Krishi Viswavidyalaya, Kalyani, Nadia, West Bengal. The soybean cultivar 'Pusa 16' (duration 110 days) was used. The pre-emergence application (PE) of diclosulam 38.7 g/ha was more effective in managing all predominant grasses, sedges and broad-leaved weeds than other tested herbicides, and recorded 34.81%, 77.1%, 51.9%, 19.2% and 53.79% more primary branches/plant, pods/plant, seeds/pod, test weight and seed yield than the weedy check. It was statistically at par with the hand weeding. Both physico-chemical and biological properties of post-harvest soil remained unaffected by herbicidal treatments. Diclosulam at varied dosages did not cause any adverse effect on germination, plant stand and yield of succeeding mustard. Thus, diclosulam 38.7 g/ha PE can be recommended for effective control of grasses, sedges and broadleaved weeds in soybean under soybean-mustard cropping system.

Keywords: Diclosulam, Mustard, Soybean, Weed management

INTRODUCTION

In West Bengal, soybean [*Glycine max* (L.) Merr.] is cultivated during *Kharif* season covering 235 hectares of land with an average productivity of 0.817 t/ha during 2022-23. However, soybean cultivated area has been declining over the last ten years from 543 ha in 2012-13 to 235 ha in 2022-23. Similarly, soybean production was also dwindled from 439 t in 2012-13 to 192 t in 2022-23. The soybean shares were only 0.05% and 0.04% of area and production of total pulses in West Bengal during 2022-23 (GoWB 2023). Hence, soybean cultivation needs scientific technological interventions for the improvement of soybean area, production and productivity.

Out of many biological constraints, weeds are the major one. Soybean normally grow very short and as a result weeds can easily smother the crop plants. Being a rainy season crop, soybean faces severe

weed competition during early stages of crop growth due to continuous infestation of grasses, sedges and broad-leaved weeds (Zion *et al.* 2025). Weeds compete directly with soybean for light, nutrients and moisture and exhibit allelopathy to reduce crop growth (Singh *et al.* 2009). Initial 45 days after sowing are the most critical for weed competition in soybean (Mishra *et al.* 2016). The yield loss of 10-100%, due to weeds, was reported depending on the weed intensity, nature, environmental condition and duration of weed competition (Rao and Chauhan 2015). Therefore, yield can be increased by keeping the soybean field weed-free during initial critical period.

Weeds and soybean crop emerge simultaneously in uplands during *Kharif* season; hence, the proper time and method of weed control are critical. A few herbicides like pre-emergence application (PE) of pendimethalin and post-emergence application (PoE) of imazethapyr, fluazifop-p-butyl and bentazone are being used to control weeds in *Kharif* soybean. However, repeated use of similar herbicides, in *Kharif* soybean, is not advisable as they have their own limitations. Pendimethalin and imazethapyr control primarily annual grass (Singh *et al.* 2009) and broad-leaved weeds only, fluazifop-p-butyl controls annual and perennial grasses only (Das and Samui 2024).

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Moreover, being a pulse crop soybean is sensitive to many herbicides. Hence, alternative herbicides needed to be identified for effective and broad-spectrum weed control, without phytotoxic effects in soybean.

Diclosulam, a novel herbicide class of triazolo pyrimidine sulphonamide was introduced to India, mainly to control weeds in soybean and groundnut. The efficacy of diclosulam for the control of broad-leaved weeds in a number of field crops (Bhattacharyya *et al.* 2012) and forestry applications (Singh *et al.* 2009) has already been established. Diclosulam can be applied preemergence but will not be effective until rainfall or irrigation has moved it into the soil where weed germination occurs (Grey *et al.* 2001). Its longevity in the soil makes diclosulam ideal for control of broad-leaved weeds in soybean (Bhattacharyya *et al.* 2012). But its use in study location has been limited due to its non-availability and hence, actual potentiality is still unknown in *Kharif* soybean cultivation. Furthermore, the dosage of diclosulam recommended for soybean cultivation may vary based on the moisture content and organic matter of the soil and factors that influence the adsorption of diclosulam. Thus, diclosulam efficacy to manage weeds in soybean under alluvial soil of West Bengal is yet to be studied. Hence, the present study was conducted with an objective to assess the efficacy of diclosulam in effectively managing complex weed flora of Soybean in Nadia, West Bengal.

MATERIALS AND METHODS

The study was conducted during *Kharif* season soybean (2020 and 2021) and succeeding mustard crop in *Rabi* season at District Seed farm-C unit, Kalyani, Nadia, West Bengal under Bidhan Chandra Krishi Viswavidyalaya (situated at 22°58' N latitude, 88°25' E longitude and 9 m above mean sea level). Medium land (water stagnation never exceeds 30 cm) was chosen for the study. The soil was sandy clay loam (27.4% sand, 44.4% silt and 28.2% clay according to Hydrometer method) in texture and had the following key properties for the 0–30 cm layer: pH 7.35 (in 1:2.5::Soil:Water), electrical conductivity (EC) 0.25 dS/m (in 1:2.5::Soil:Water), organic carbon 0.50% (wet oxidation method), available N 182.1 kg/ha (Hot alkaline KMnO₄ Method), available P 78.3 kg/ha (0.5 M NaHCO₃ extract) and available K 193.2 kg/ha (Neutral N NH₄OAc extract). The study location had sub-humid and sub-tropical climate with an average annual rainfall of 1200 mm, 80% of which falls during rainy season (June to September) due to

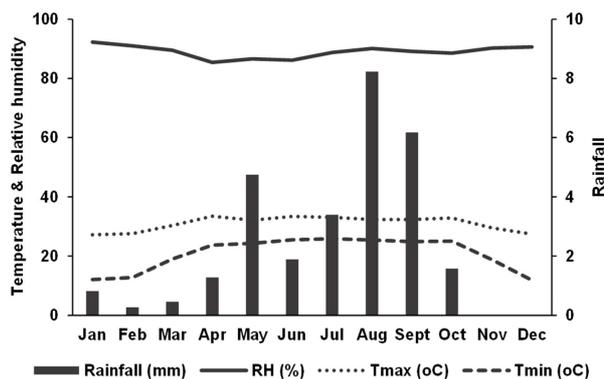


Figure 1. Monthly temperature, relative humidity and rainfall recorded at experimental site (average of 2-years data)

south-west monsoon. Weather data were logged at Automated Weather Station (AWS), Directorate of Research, BCKV, Kalyani, Nadia. Meteorological parameters, based on 2-years average, pertaining to the period of experimentation have been depicted in **Figure 1**. Average monthly maximum and minimum temperatures fluctuated between 27.22 and 33.47°C, and 11.85 and 25.84°C, respectively. Average relative humidity ranged from 85.40 to 92.29%. Total average rainfall was 28.856 mm; however, there was no rain in November and December months.

There were 8 treatments: diclosulam 22.01 g/ha, 3 days after seeding (DAS); diclosulam 25.95 g/ha, 3 DAS; diclosulam 32.50 g/ha, 3 DAS; diclosulam 22.01 g/ha, 3 DAS; diclosulam 25.96 g/ha, 3 DAS; imazethapyr + surfactant 100 g/ha MSO adjuvant 2 ml/L water, 10 DAS; hand weeding twice 20 and 40 DAS and untreated control (weedy check), Herbicides were sprayed by using 500 liters of water/ha.

A randomized complete block design (RCBD) with three replications was used. The soybean cultivar '*Pusa 16*' (duration 110 days) was sown during *Kharif* season on 5th July. Seeds were sown at a spacing of 45 cm × 5 cm in every single plot (4 m × 5 m). On maturity, the crop was harvested on 23rd October. All the recommended improved package of practices of soybean crop was followed in this experiment including the plant protection measures. All the test herbicides were sprayed at the given time using a water volume of 500-600 liters/ha with knapsack sprayer fitted with flat fan deflector nozzle. Weed free treatment was maintained by hand weeding at regular interval. After harvesting of soybean crop, mustard (cv. B-9/Binoy) was sown 5 kg/ha in the undisturbed field layout of trial plot with a spacing of 30 cm × 10 cm on 28th October. The crop was allowed to grow with recommended package of practices suitable for the region and was harvested on

5th January. The mustard crop received no herbicidal treatments for weed control and the residual effect of herbicidal treatments adopted for preceding soybean crop was assessed. The population of weeds (weed density) was recorded species-wise at 30 days after sowing (DAS), 45 DAS and 60 DAS. A quadrat of 1 m × 1 m size was placed randomly at five spots in each plot and the weeds from that area were counted and expressed as weed density (no./m²). Predominant weeds belonging to three categories (grasses, sedges and broad-leaved weeds) obtained in population at the respective days were labeled properly. The labeled samples were then sun dried for 24 hours and then oven-dried at 70°C for 72 hours. The dry weight of weeds (weed biomass) was then recorded species-wise separately.

Weed control efficiency is expressed as the percentage of control of weeds over unweeded control on dry weight basis by using the following formula.

$$WCE = \frac{DWC - DWT}{DWC} \times 100$$

Where, DWC = Weed biomass in untreated control plot; DWT = Weed biomass in treated plot with herbicide

The data on grain yield and haulm yield were recorded for soybean. Both grain and haulm yield of soybean was recorded plot-wise after threshing and then converted in t/ha.

Observation on follow-up crop *i.e.*, mustard raised in undisturbed layout of trial plot, was recorded

with respect to previously applied different doses of diclosulam at 26.2, 30.9 and 38.7 g/ha along with market standard samples. The observations on crop emergence, plant stand, yield and symptoms of phytotoxicity were recorded at 15 DAS, 30 DAS and at harvest. Finally, grain yields were recorded at harvest.

As wide variation existed in number of weeds, data were transformed through square-root $\sqrt{x+0.5}$ method before statistical analysis. All the collected data were analyzed statistically by the method of analysis of variance (ANOVA) as per the procedure outlined for randomized complete block design (Gomez and Gomez 1984). Statistical significance was tested by P-value at 0.05 level of probability and critical difference (CD) was worked out wherever the effects were significant.

RESULTS AND DISCUSSION

Effect on weeds

Broad-leaved weeds: *Euphorbia geniculata*, *Digera arvensis*, *Commelina benghalensis*, and *Acalypha indica*, as well as grassy weeds like *Echinochloa colona* and the sedge *Cyperus rotundus* were found to be infesting soybean. The hand weeding twice was the most effective treatment in terms of weed density reduction at 30, 45 and 60 DAS (**Table 2**). Diclosulam 38.7 g/ha was the most effective at controlling weeds and reducing weed density and biomass (**Table 2**) with higher weed control efficiency (**Table 3**), among all herbicide treatments

Table 1. Density of grasses, sedges and broad-leaved weeds (no./m²) in soybean field as affected by treatments during Kharif season (pooled data of 2 years)

Treatment	<i>Echinochloa colona</i>		<i>Cyperus rotundus</i>		<i>Euphorbia geniculata</i>		<i>Digera arvensis</i>		<i>Commelina benghalensis</i>		<i>Acalypha indica</i>		Total	
	30	60	30	60	30	60	30	60	30	60	30	60	30	60
	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS
Diclosulam 22.01 g/ha, 3 DAS	1.72** (2.45*)	2.35** (5.04*)	1.57 (1.96)	2.18 (4.25)	1.47 (1.65)	2.48 (5.65)	1.35 (1.32)	2.60 (6.25)	1.12 (0.75)	2.47 (5.62)	1.17 (0.86)	2.27 (4.66)	8.40 (8.99)	14.35 (31.47)
Diclosulam 25.95 g/ha, 3 DAS	1.55 (1.89)	2.13 (4.05)	1.23 (1.01)	2.00 (3.52)	1.40 (1.44)	2.27 (4.66)	1.24 (1.04)	2.18 (4.26)	1.07 (0.64)	2.15 (4.11)	1.10 (0.72)	2.09 (3.86)	7.59 (6.74)	12.82 (24.46)
Diclosulam 32.50 g/ha, 3 DAS	1.23 (1.01)	1.86 (2.96)	1.06 (0.62)	1.58 (2.01)	1.16 (0.85)	1.88 (3.02)	1.12 (0.75)	1.90 (3.11)	1.00 (0.51)	1.78 (2.66)	1.02 (0.55)	1.87 (3.01)	6.57 (4.29)	10.87 (16.77)
Diclosulam 22.01 g/ha, 3 DAS	2.60 (6.25)	3.28 (10.26)	1.90 (3.12)	3.15 (9.44)	1.75 (2.56)	3.03 (8.69)	1.72 (2.45)	3.17 (9.56)	1.87 (2.99)	3.18 (9.60)	1.58 (1.99)	2.83 (7.52)	11.42 (19.36)	18.64 (55.07)
Diclosulam 25.96 g/ha, 3 DAS	2.51 (5.82)	3.08 (8.99)	1.78 (2.66)	2.95 (8.20)	1.62 (2.11)	2.75 (7.06)	1.48 (1.69)	2.99 (8.45)	1.70 (2.40)	2.83 (7.52)	1.42 (1.52)	2.59 (6.23)	10.51 (16.20)	17.19 (46.45)
Imazethapyr + surfactant 100 g/ha, 10 DAS	2.13 (4.05)	3.10 (9.14)	2.07 (3.78)	2.91 (7.99)	1.86 (2.96)	3.11 (9.15)	1.58 (1.99)	2.76 (7.14)	1.76 (2.59)	3.02 (8.65)	1.68 (2.33)	2.82 (7.48)	11.08 (17.7)	17.72 (49.55)
Hand weeding twice 20 and 40 DAS	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)
Untreated control (weedy check)	5.74 (32.44)	7.50 (55.68)	3.15 (9.42)	4.02 (15.69)	2.80 (7.33)	3.98 (15.32)	2.99 (8.42)	3.82 (14.12)	2.84 (7.55)	3.75 (13.55)	2.65 (6.53)	3.81 (14.05)	20.17 (71.69)	26.88 (128.41)
LSD (p=0.05)	0.27	0.25	0.15	0.37	0.21	0.35	0.10	0.26	0.06	0.34	0.07	0.20	0.86	1.77

*Data in the parentheses are original values; **Square root transformed value of $\sqrt{x+0.5}$ was used for statistical analysis; DAS, days after sowing

as reported earlier by Singh *et al.* (2009); Musa *et al.* 2022. Next effective treatments were diclosulam 30.9 and 26.2 g/ha. Diclosulam 30.9 g/ha was found to be superior than imazethapyr + surfactant 100 g/ha in reducing weed density and biomass. Significantly higher weed biomass was recorded with un-weeded check. The broad-spectrum efficacy of diclosulam was attributed to its ability to suppress weed growth across different taxonomic groups (Sridhar *et al.* 2021). Reddy (2000) reported that diclosulam either as pre-plant incorporation (PPI) or pre-emergence application (PE) effectively controlled key broad-leaved weeds and some grasses, resulting in higher soybean yields.

Effect on soybean yield attributes and yield

Diclosulam 38.7 g/ha recorded 34.81%, 77.1%, 51.9% and 19.2% more primary branches/plant, pods/plant, seeds/pod and test weight than the weedy check and recorded higher yield attributes than other

treatments (Table 4). Next best was diclosulam 30.9 g/ha. Better vegetative and reproductive growth of crop under diclosulam 32.50 g/ha, 3 DAS treatment might have achieved due to better weed control (Musa *et al.* 2022, Das and Samui 2024). The yield attributes of soybean crop were drastically reduced in the weedy check plots due to severe weed competition confirming Rao *et al.* (2000). Compared to the unweeded control, all weed management methods considerably enhanced seed and haulm yield (Table 4). Diclosulam 38.7 g/ha provided statistically greater yield than other treatments followed by diclosulam 30.9 g/ha. When compared to the weedy check, the soybean seed yield has increased by 53.79% and 37.24% with diclosulam 38.7 g/ha and 30.9 g/ha respectively. In contrast, lowest seed yield of soybean was observed in weedy check plots because of heavy weed infestation vis-à-vis severe crop-weed competition and huge exploitation of growth factors by the weeds.

Table 2. Biomass of grasses, sedges and broad-leaved weeds (g/m²) in soybean as affected by treatments during Kharif season (pooled data of 2 years)

Treatment	<i>Echinochloa colona</i>		<i>Cyperus rotundus</i>		<i>Euphorbia geniculata</i>		<i>Digera arvensis</i>		<i>Commelina benghalensis</i>		<i>Acalypha indica</i>		Total	
	30	60	30	60	30	60	30	60	30	60	30	60	30	60
	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS
Diclosulam 22.01 g/ha, 3 DAS	4.56	8.55	3.01	7.26	3.16	8.66	2.99	7.56	3.55	10.20	3.22	8.15	20.49	50.38
Diclosulam 25.95 g/ha, 3 DAS	3.24	6.59	2.46	5.68	2.88	6.96	2.45	6.23	3.01	8.01	2.88	7.01	16.92	40.48
Diclosulam 32.50 g/ha, 3 DAS	1.42	4.26	1.99	4.06	1.89	4.03	1.64	3.96	1.48	5.03	1.76	4.56	10.18	25.90
Diclosulam 22.01 g/ha, 3 DAS	8.22	12.46	3.05	8.96	4.01	11.26	4.50	9.56	4.96	13.26	2.96	9.10	27.70	64.60
Diclosulam 25.96 g/ha, 3 DAS	7.86	11.86	3.01	7.66	3.99	10.69	4.10	9.00	4.22	12.01	2.86	9.00	26.01	60.22
Imazethapyr + surfactant 100 g/ha, 10 DAS	8.46	12.30	3.60	10.69	4.15	10.68	3.99	8.69	5.01	11.36	3.77	11.24	28.98	64.96
Hand weeding twice 20 and 40 DAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Untreated control (weedy check)	28.46	35.80	12.25	20.15	15.02	22.36	18.01	24.01	16.42	25.23	11.40	15.63	101.56	143.18
LSD (p=0.05)	1.78	1.96	0.45	1.46	0.88	2.01	0.72	1.28	0.85	2.00	0.95	1.85	5.63	10.56

DAS, days after sowing

Table 3. Weed control efficiency (%) against grasses, sedges and broad-leaved weeds in soybean as affected by treatments during Kharif season (pooled data of 2 years)

Treatment	<i>Echinochloa colona</i>		<i>Cyperus rotundus</i>		<i>Euphorbia geniculata</i>		<i>Digera arvensis</i>		<i>Commelina benghalensis</i>		<i>Acalypha indica</i>		Total	
	30	60	30	60	30	60	30	60	30	60	30	60	30	60
	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS	DAS
Diclosulam 22.01 g/ha, 3 DAS	83.98	76.12	75.43	63.97	78.96	61.27	83.40	68.51	78.38	59.57	71.75	47.86	79.82	64.81
Diclosulam 25.95 g/ha, 3 DAS	88.62	81.59	79.92	71.81	80.83	68.87	86.40	74.05	81.67	68.25	74.74	55.15	83.34	71.73
Diclosulam 32.50 g/ha, 3 DAS	95.01	88.10	83.76	79.85	87.42	81.98	90.89	83.51	90.99	80.06	84.56	70.83	89.98	81.91
Diclosulam 22.01 g/ha, 3 DAS	71.12	65.20	75.10	55.53	73.30	49.64	75.01	60.18	69.79	47.44	74.04	41.78	72.73	54.88
Diclosulam 25.96 g/ha, 3 DAS	72.38	66.87	75.43	61.99	73.44	52.19	77.23	62.52	74.30	52.40	74.91	42.42	74.39	57.94
Imazethapyr + surfactant 100 g/ha, 10 DAS	70.27	65.64	70.61	46.95	72.37	52.24	77.85	63.81	69.49	54.97	66.93	28.09	71.47	54.63
Hand weeding twice 20 and 40 DAS	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Untreated control (weedy check)	-	-	-	-	-	-	-	-	-	-	-	-	-	-

DAS, days after sowing

Table 4. Yield attributes and yield of *Kharif* soybean and mustard in succession as affected by treatments tested in soybean (pooled data of 2 years)

Treatment	Soybean						Seedling Emergence (%) at 15 DAS	Mustard			Seed yield (kg /ha)
	Yield attributes				Yield (t/ha)			Plant stand (nos./m ²)			
	Primary branches / plant	Pods/ plant	Seeds/ pod	Test weight (g)	Seed	Haulm		15 DAS	30 DAS	Harvest	
Diclosulam 22.01 g/ha, 3 DAS	3.31	55	2.40	131	1.71	3.61	100	33	32	32	760
Diclosulam 25.95 g/ha, 3 DAS	3.43	58	2.65	136	1.99	3.91	100	33	33	33	801
Diclosulam 32.50 g/ha, 3 DAS	3.64	62	3.19	143	2.23	4.30	100	33	33	33	945
Diclosulam 22.01 g/ha, 3 DAS	3.30	56	2.41	132	1.50	3.40	100	33	31	31	690
Diclosulam 25.96 g/ha, 3 DAS	3.41	57	2.51	135	1.60	3.45	100	33	32	31	750
Imazethapyr + surfactant 100 g/ha, 10 DAS	3.39	57	2.45	139	1.85	3.70	100	33	33	33	807
Hand weeding twice 20 and 40 DAS	3.72	64	3.24	145	2.35	4.35	100	33	33	33	970
Untreated control (weedy check)	2.70	35	2.10	120	1.45	2.90	100	33	32	31	490
LSD (p=0.05)	0.09	2.10	0.06	2.12	0.14	0.07	-	-	-	-	27.00

DAS, Days after sowing

Table 5. Soil (0-15 cm) physico-chemical properties and status of soil micro-flora after *Kharif* soybean harvest as affected by treatments (pooled data of 2 years)

Treatment	Physico-chemical properties						Soil micro-flora (cfu × 10 ⁶ /g of soil)		
	pH	EC (dS/m)	OC (%)	Av. N (kg/ha)	Av. P (kg/ha)	Av. K (kg/ha)	Bacteria	Fungi	Actinomycetes
Diclosulam 22.01 g/ha, 3 DAS	7.32	0.21	0.51	88.51	75.33	199.52	74.52	24.51	21.45
Diclosulam 25.95 g/ha, 3 DAS	7.12	0.24	0.55	85.02	72.24	194.25	76.82	26.33	22.59
Diclosulam 32.50 g/ha, 3 DAS	7.44	0.25	0.54	91.24	74.01	195.63	85.42	30.56	24.51
Diclosulam 22.01 g/ha, 3 DAS	7.32	0.29	0.60	88.21	72.12	201.45	73.26	24.00	20.12
Diclosulam 25.96 g/ha, 3 DAS	7.40	0.31	0.53	84.56	70.14	200.53	66.85	23.14	21.38
Imazethapyr + surfactant 100 g/ha, 10 DAS	7.51	0.24	0.59	90.50	70.34	194.22	68.77	20.15	20.20
Hand weeding twice 20 and 40 DAS	7.49	0.30	0.52	85.46	74.55	191.25	75.96	29.56	23.56
Untreated control (weedy check)	7.27	0.28	0.55	86.21	71.42	196.28	62.38	20.77	21.44
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAS, Days after sowing; NS, Non-significant

Effect on physico-chemical properties and microbial population of soil

The physico-chemical properties of soil like pH, EC and organic carbon were not significantly influenced by the herbicidal treatments compared to initial status of soil (Table 5). Available soil N (91.24 kg/ha), P (75.33 kg/ha) and K status (201.45 kg/ha) in post-harvest soil was increased with diclosulam 38.7 g/ha, diclosulam 26.2 g/ha and diclosulam 26.2 g/ha compared to initial status. Total micro flora population has increased with diclosulam 38.7 g/ha (Table 5). Total bacterial, fungal and actinomycetes population was changed from 74.86 cfu × 10⁶/g (initial) to 85.42 cfu × 10⁶/g (final), 24.59 cfu × 10⁶/g (initial) to 30.56 cfu × 10⁶/g (final) and 22.43 cfu × 10⁶/g (initial) to 24.51 cfu × 10⁶/g (final) respectively as microorganisms engaged in the process of herbicide breakdown which released carbon-rich substrates that boost the number of soil microorganisms (Das and Samui 2024).

Effect on emergence, plant stand and yield of succeeding mustard crop

The emergence percent of mustard crop was not affected due to different herbicidal treatments applied in the preceding *Kharif* soybean (Table 4). On the other hand, the herbicidal treatments applied in soybean resulted in significant improvements/ variations in seed yield of succeeding crop mustard (Table 4). The treatments that were effective in soybean also recorded the highest mustard seed yield. Diclosulam 38.7 g/ha PE applied in soybean has recorded significantly higher mustard seed yield which was 92.9% higher yield over untreated control (weedy check), due to its longer persistence in soil with slight residual effects on weeds in the succeeding mustard crop.

Conclusion

Diclosulam 38.7 g/ha PE can be recommended for effective control of grasses, sedges and broad-leaved weeds in *Kharif* soybean cultivation in alluvial soil of West Bengal.

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RESEARCH ARTICLE

Integrated weed management options in *Kharif* groundnut

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ABSTRACT

A field experiment was conducted during *Kharif* seasons of 2022–2024 to evaluate the integrated weed management options and identify effective and economic option in groundnut. The pre-emergence application (PE) of oxyfluorfen + pendimethalin (tank-mix) 188 + 500 g/ha followed by (*fb*) intercultural operation (IC) and hand weeding (HW) at 40 days after seeding (DAS) recorded the lowest weed biomass. The tallest groundnut plants and pod yield was observed with IC *fb* HW at 20 and 40 DAS and diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE *fb* IC + HW at 40 DAS. Pendimethalin + imazethapyr (ready-mix) 800 g/ha PE and diclosulam + pendimethalin (tank-mix) 25.2 + 500 g/ha (PE) recorded higher weed management indices values. The other effective weed control options, under labour-scarce conditions, in groundnut include: IC *fb* HW at 20 and 40 DAS; quizalofop ethyl + imazethapyr (ready-mix) 90 g/ha and post-emergence application (PoE) propaquizafop + imazethapyr (ready-mix) 125 g/ha integrated with IC + HW at 40 DAS.

Keywords: Diclosulam + pendimethalin; Groundnut, Pendimethalin + imazethapyr; Propaquizafop + imazethapyr; Quizalofop ethyl + imazethapyr Weed management

INTRODUCTION

Groundnut (*Arachis hypogaea* L.), commonly known as peanut, is a vital edible oilseed crop in India and belongs to the family Leguminosae. Its kernels, rich in oil (47–49%) and protein (around 20%) are highly digestible and typically consumed as roasted, fried or salted. In the 2022–23 season, India produced 10.30 m t of groundnut with a productivity of 2.075 t/ha (Anon 2023). Major groundnut-producing states include Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka, Maharashtra, Madhya Pradesh, Uttar Pradesh, Rajasthan, Punjab and Odisha. Despite its economic importance, groundnut production is often hampered by suboptimal agronomic practices and inadequate weed management.

Groundnut fields typically infested with mix of narrow-leaf weeds, broad-leaved weeds and sedges. Due to its slow initial growth, short stature and underground pod development, groundnut is particularly vulnerable to weed infestation. The critical period of crop-weed control is 4–9 weeks after sowing for grasses and 3–6 weeks for broad-leaved weeds (Wesley et al. 2008). The groundnut fields are invaded by a wide range of weed species

including grasses, broad-leaved weeds and sedges, which can lead to significant yield reductions ranging from 30% to 80% (Rao *et al.* 2014). Effective and timely weed control is therefore, essential to realize the groundnut yield potential.

The selective herbicides may suppress specific group of weeds, but often failed to control complex weed flora, which varies with agro-ecological conditions and management practices. Pre-emergence herbicides offer limited duration of control, allowing late-emerging weeds to escape from the applied herbicide. Hence, integrating herbicide application with sound cultural practices is crucial for managing weeds and boosting *Kharif* groundnut productivity. Thus, a study was conducted to evaluate the effectiveness of integrated weed management options, with herbicide mixtures as component, in controlling weeds and enhancing *Kharif* groundnut productivity.

MATERIALS AND METHODS

A field experiment was conducted during three consecutive *Kharif* season of the year 2022, 2023 and 2024 in loamy sand soil of AICRP on Weed Management Farm, B. A. College of Agriculture, Anand Agricultural University, Anand, Gujarat state, India. The soil of the experimental field was low in available nitrogen and medium in available phosphorous and high in potassium. Twelve weed

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management were tested including: pre-emergence application (PE) of pendimethalin 30% EC 750 g/ha followed by (fb) inter-cultivation (IC) + hand weeding (HW) at 40 days after seeding (DAS), flumioxazin 50% SC (flumioxazin) 125 g/ha fb IC + HW at 40 DAS, diclosulam 84% WDG (diclosulam) 25.2 g/ha PE fb IC + HW at 40 DAS, Oxyfluorfen 23.5% EC (oxyfluorfen) + pendimethalin (tank-mix) 188+500 g/ha PE fb IC + HW at 40 DAS, diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE fb IC + HW at 40 DAS, pendimethalin 30% + imazethapyr 2% EC (pendimethalin + imazethapyr) (ready-mix) 800 g/ha PE fb IC + HW at 40 DAS, sodium-acifluorfen 16.5% + clodinafop-propargyl 8% EC (sodium-acifluorfen + clodinafop-propargyl) (ready-mix) 245 g/ha PoE fb IC + HW at 40 DAS, fluzifop-p-butyl 11.1% w/w + fomesafen 11.1% w/w SL (fluzifop-p-butyl + fomesafen) (ready-mix) 250 g/ha PoE fb IC + HW at 40 DAS, propaquizafop 2.5% + imazethapyr 3.75% w/w ME (propaquizafop + imazethapyr) (ready-mix) 125 g/ha PoE fb IC + HW at 40 DAS, quizalofop-ethyl 7.5% + imazethapyr 15% w/w EC (quizalofop-ethyl + imazethapyr) (ready-mix) 90 g/ha PoE fb IC + HW at 40 DAS, IC fb HW at 20 and 40 DAS and weedy check. A randomized block design with three replications was used.

The groundnut variety GG 34 was sown on 16th June, 23rd June and 20th July 2022, 2023 and 2024, respectively with a row spacing of 30 x 10 cm, using seed rate of 120 kg/ha. Fertilization was done using the recommended basal dose of 12.5 kg N and 25 kg P, O... /ha applied through urea and single super phosphate, respectively. All other recommended agronomic practices were followed to ensure optimal crop growth. Pre-emergence herbicides were applied the day after sowing and post-emergence herbicides were sprayed at 20 DAS using a battery-operated knapsack sprayer equipped with a flat-fan nozzle with 500 liters of water/ha. Weed density and dry weight (biomass) were assessed through destructive sampling at four randomly selected spots within the net plot using a 0.25 m² iron quadrat. Additional observations on crop growth and yield attributes were also recorded from the net plot area. All collected data were statistically analyzed following the standard procedures outlined by Cochran and Cox (1957).

Weed Control Efficiency (WCE), weed Index (WI), weed persistence index (WPI), agronomic management index (AMI), weed management index (WMI) and integrated weed management index (IWMI) were calculated using the formula given by Sharma (2017) are as under:

$$WCE (\%) = \frac{DWC - DWT}{DWC} \times 100$$

Where, DWC= Dry weight of weeds in unweeded control plot
DWT= Dry weight of weeds in treated plot.

$$WI (\%) = \frac{X - Y}{X} \times 100$$

Where, X= Highest yield from treatment
Y= Yield from particular treatment

$$WPI = \frac{W_T}{W_C} \times \frac{W_{PC}}{W_{PT}}$$

Where, W_c = Weed dry weight in unweeded control plot
W_T = Weed dry weight in treated plot
W_{PC} = Weed population in unweeded control plot
W_{PT} = Weed population in treated plot

$$AMI = \frac{Y_T - Y_C}{W_C - W_T} \times \frac{W_C - E_T}{W_C}$$

Where, Y_T = Yield from treated plot
Y_C = Yield from unweeded control plot
W_c = Weed dry weight in unweeded control plot
W_T = Weed dry weight in treated plot

$$WMI = \frac{Y_T - Y_C}{W_C - W_T} \times \frac{W_C}{W_C}$$

Where, Y_T = Yield from treated plot
Y_C = Yield from unweeded control plot
W_c = Weed dry weight in unweeded control plot
W_T = Weed dry weight in treated plot

$$IWMI = \frac{WMI + AMI}{2}$$

Where, WMI= Weed management index
AMI = Agronomic management index

RESULTS AND DISCUSSION

Effect on weeds

The experimental field was dominated by diverse weed flora consisting of both broad-leaved and grassy weeds. The grassy weeds accounted for 47% and broad-leaved weeds for 43% of the total weeds. *Digitaria sanguinalis*, *Commelina benghalensis*, *Dactyloctenium aegyptium* and *Eleusine indica* were monocot weeds while *Digera arvensis*, *Phyllanthus niruri*, *Oldenlandia umbellate* and *Trianthema monogyna* were dicot weeds that dominated the experimental field during three years of experimentation.

Weed biomass at 60 DAS showed considerable variation across treatments and years (Table 1). The weedy check recorded significantly the highest weed biomass and the lowest values were recorded with oxyfluorfen + pendimethalin 188 + 500 g/ha PE *fb* IC + HW at 40 DAS, which provided broad-spectrum control of both grassy and broad-leaved weeds. This integrated approach is particularly effective in groundnut as it ensured suppression of late-emerging weeds and maintaining a weed-free environment throughout the crop’s growth period. The ready-mix combination of pendimethalin + imazethapyr 800 g/ha PE *fb* IC + HW at 40 DAS also caused notable reduction of weed dry biomass. Confirming findings of Venkateshwara *et al.* (2020). Other treatments

such as diclosulam 25.2 g/ha PE *fb* IC + HW at 40 DAS, sodium-acifluorfen + clodinafop-propargyl (ready-mix) 245 g/ha PoE *fb* IC + HW at 40 DAS, fluazifop-p-butyl + fomesafen (ready-mix) 250 g/ha PoE *fb* IC + HW at 40 DAS, propaquizafop + imazethapyr (ready-mix) 125 g/ha PoE *fb* IC + HW at 40 DAS, quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha PoE *fb* IC + HW at 40 DAS and IC *fb* HW at 20 and 40 DAS were next best in the order of reducing weed biomass. Similar results were recorded at groundnut harvest.

Effect on weed indices

Pendimethalin + imazethapyr (ready-mix) 800 g/ha *fb* IC + HW at 40 DAS and diclosulam +

Table 1. Weed biomass and weed control efficiency by weed management treatments in Kharif groundnut

Treatment	Weed biomass at 60 DAS (g/m ²)			Weed biomass at harvest (g/m ²)			Weed control efficiency (%) at harvest		
	2022	2023	2024	2022	2023	2024	2023	2024	Average
Pendimethalin 750 g/ha PE <i>fb</i> IC + HW at 40 DAS	6.06(36.5)	4.36(18.1)	3.56(11.8)	8.80(77.2)	7.13(52.4)	5.61(30.7)	85.48	89.52	80.90
Flumioxazin 125 g/ha PE <i>fb</i> IC + HW at 40 DAS	5.73(31.9)	3.41(10.8)	3.09(8.67)	9.06(84.6)	6.17(37.2)	5.63(30.7)	89.70	89.52	81.27
Diclosulam 25.2 g/ha PE <i>fb</i> IC + HW at 40 DAS	5.37(28.0)	4.41(20.1)	4.63(20.5)	6.61(43.7)	7.24(52.0)	6.86(46.3)	85.60	84.20	83.84
Oxyfluorfen + pendimethalin (tank-mix) 188+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	4.51(19.4)	2.97(7.84)	2.46(5.20)	6.05(35.7)	7.09(49.4)	4.71(21.6)	86.32	92.63	88.00
Diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	5.07(24.7)	3.75(14.1)	3.72(12.9)	6.77(44.8)	7.76(59.7)	5.94(34.5)	83.46	88.23	84.32
Pendimethalin + imazethapyr (ready-mix) 800 g/ha PE <i>fb</i> IC + HW at 40 DAS	4.53(19.7)	3.59(12.1)	2.95(7.73)	5.45(29.2)	7.04(52.1)	5.48(29.5)	85.57	89.93	87.76
Sodium-acifluorfen + clodinafop-propargyl (ready-mix) 245 g/ha PoE <i>fb</i> IC + HW at 40 DAS	6.15(36.8)	3.57(12.0)	4.30(17.6)	6.60(42.9)	6.93(50.3)	7.14(50.0)	86.07	82.94	83.69
Fluazifop-p-butyl + fomesafen (ready-mix) 250 g/ha PoE <i>fb</i> IC + HW at 40 DAS	5.23(26.5)	3.17(9.16)	4.03(15.5)	6.01(35.2)	7.19(52.4)	7.90(61.9)	85.48	78.87	83.21
Propaquizafop + imazethapyr (ready-mix) 125 g/ha PoE <i>fb</i> IC + HW at 40 DAS	5.63(31.1)	3.09(8.56)	3.44(10.8)	8.97(80.0)	6.38(40.5)	5.79(32.5)	88.78	88.91	81.41
Quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha PoE <i>fb</i> IC + HW at 40 DAS	4.77(21.9)	3.85(13.9)	4.53(19.7)	7.77(59.8)	7.91(63.1)	7.00(48.1)	82.52	83.58	80.36
IC <i>fb</i> HW at 20 and 40 DAS	4.65(20.7)	3.41(11.0)	4.37(18.2)	8.09(64.5)	6.84(47.3)	6.99(48.1)	86.90	83.58	81.16
Weedy check	18.0(323)	16.1(258)	16.8(284)	15.5(239)	19.0(361)	17.1(293)	-	-	-
F test	0.86	1.34	0.98	1.70	2.37	1.04	-	-	-

Note: Data subjected to ($\sqrt{x+1}$) transformation. Figures in parentheses are means of original values. ; DAS = days after seeding; PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by; IC = inter-cultivation; HW = hand weeding

Table 2. Groundnut pod yield as influenced by weed management treatments in Kharif groundnut

Treatment	Groundnut plant height (cm) at harvest			Groundnut pod yield (kg/ha)				Benefit: cost ratio
	2022	2023	2024	2022	2023	2024	Pooled	
Pendimethalin 750 g/ha PE <i>fb</i> IC + HW at 40 DAS	58.0	71.1	61.3	2753	4128	2987	3289	2.49
Flumioxazin 125 g/ha PE <i>fb</i> IC + HW at 40 DAS	61.7	68.4	61.0	2413	4056	2973	3148	2.34
Diclosulam 25.2 g/ha PE <i>fb</i> IC + HW at 40 DAS	65.9	69.9	62.0	2730	3740	2230	2900	2.20
Oxyfluorfen + pendimethalin (tank-mix) 188+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	68.8	69.7	57.7	2313	3857	2673	2948	2.32
Diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	66.4	73.8	61.7	2690	4059	3017	3255	2.55
Pendimethalin + imazethapyr RM 800 g/ha PE <i>fb</i> IC + HW at 40 DAS	64.9	72.4	64.5	2380	4106	2428	2971	2.34
Sodium-acifluorfen + clodinafop-propargyl RM 245 g/ha PoE <i>fb</i> IC + HW at 40 DAS	65.1	71.9	63.1	2477	3946	2418	2947	2.24
Fluazifop-p-butyl + fomesafen RM 250 g/ha PoE <i>fb</i> IC + HW at 40 DAS	64.1	72.6	62.8	2467	3974	2295	2912	2.21
Propaquizafop + imazethapyr RM 125 g/ha PoE <i>fb</i> IC + HW at 40 DAS	67.6	72.9	63.5	2400	4027	3400	3276	2.50
Quizalofop-ethyl + imazethapyr RM 90 g/ha PoE <i>fb</i> IC + HW at 40 DAS	69.3	72.6	63.3	2413	3891	3217	3174	2.44
IC <i>fb</i> HW at 20 and 40 DAS	66.5	73.1	64.4	2850	3924	3423	3399	2.38
Weedy check	73.8	81.3	71.3	363	855	217	478	0.43
F test	7.51	4.08	NS	458	502	64.60	487	-

Note: Data subjected to ($\sqrt{x+1}$) transformation. Figures in parentheses are means of original values. ; DAS = days after seeding; PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by; IC = inter-cultivation; HW = hand weeding; RM: ready-mix

pendimethalin (tank-mix) 25.2+500 g/ha *fb* IC + HW at 40 DAS consistently recorded high WCE values, low WI and WPI scores and favourable AMI and IWMI. These treatments effectively managed early emerged weeds, minimized regrowth of the weeds and reduced groundnut yield losses due to weeds. Notably, flumioxazin 125 g/ha *fb* IC + HW at 40 DAS and oxyfluorfen + pendimethalin (tank-mix) 188+500 g/ha *fb* IC + HW at 40 DAS also were effective in controlling weeds, especially in the year 2023 and 2024.

The interaction of inter-cultivation followed by hand weeding (IC *fb* HW at 20 and 40 DAS) has emerged as an excellent weed management option and recorded superior IWMI and WMI values. Lakshmidevi *et al.* (2022) also observed higher WCE in groundnut with inter-cultivation twice followed by hand weeding at 20 and 40 DAS. In resource-constrained scenarios particularly paucity of labours, quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha *fb* IC + HW at 40 DAS and propaquizafop + imazethapyr (ready-mix) 125 g/ha *fb* IC + HW at 40 DAS found to be viable option to attain high weed control efficiency with reduced labour dependency and confirmed observations of Suryavanshi *et al.* (2018) in blackgram.

Effect on groundnut

Phytotoxicity of applied herbicide on groundnut was recorded at 7 days after application. The

oxyfluorfen + pendimethalin (tank-mix), sodium-acifluorfen + clodinafop-propargyl and fluzafop-p-butyl + fomesafen showed phytotoxic effect of groundnut leaf injury (score-1) but it was recovered at 14 days after herbicide application. Other applied herbicides were not phytotoxic groundnut.

In terms of crop vigour as indicated by groundnut plant height, significant differences were recorded in 2022 and 2023 whereas, no statistical significance was observed in 2024. IC *fb* HW at 20 and 40 DAS and diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha *fb* IC + HW at 40 DAS recorded the tallest plants during 2022 and 2023, respectively. Groundnut pod yield was significantly influenced by weed management treatments in all years. In 2022 and 2024, IC *fb* HW at 20 and 40 DAS produced significantly higher groundnut pod yield which was followed by diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha *fb* IC + HW at 40 DAS, propaquizafop + imazethapyr (ready-mix) 125 g/ha *fb* IC + HW at 40 DAS and quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha *fb* IC + HW at 40 DAS. In 2023, pendimethalin 750 g/ha *fb* IC + HW at 40 DAS recorded significantly higher groundnut pod yield which was statistically at par with flumioxazin 125 g/ha *fb* IC + HW at 40 DAS, diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha *fb* IC + HW at 40 DAS and quizalofop-ethyl 7.5% + imazethapyr (ready-mix) 90 g/ha *fb* IC + HW at 40 DAS. Integrating herbicide application with mechanical

Table 3. Effect of different treatments on weed index, weed persistence index (WPI) and agronomic management index (AMI)

Treatment	Weed index (%)				Weed persistence index (WPI) at 60 DAS				Agronomic management index (AMI)			
	2022	2023	2024	Average	2022	2023	2024	Average	2022	2023	2024	Average
Pendimethalin 750 g/ha PE <i>fb</i> IC + HW at 40 DAS	3.40	-	12.74	5.38	6.51	1.28	2.83	3.54	12.99	3.48	13.26	9.91
Flumioxazin 125 g/ha PE <i>fb</i> IC + HW at 40 DAS	15.33	1.74	13.15	10.07	3.84	1.99	3.39	3.07	11.65	3.17	13.19	9.34
Diclosulam 25.2 g/ha PE <i>fb</i> IC + HW at 40 DAS	4.21	9.40	34.85	16.15	2.80	1.04	2.08	1.97	10.48	2.94	10.02	7.81
Oxyfluorfen + pendimethalin (tank-mix) 188+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	18.84	6.56	21.91	15.77	3.83	3.35	4.33	3.84	8.16	3.07	11.22	7.48
Diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	5.61	1.67	11.86	6.38	2.66	2.14	4.11	2.97	10.36	3.49	13.63	9.16
Pendimethalin + imazethapyr (ready-mix) 800 g/ha PE <i>fb</i> IC + HW at 40 DAS	16.49	0.53	29.07	15.36	5.94	2.36	6.34	4.88	8.17	3.44	10.33	7.31
Sodium-acifluorfen + clodinafop-propargyl (ready-mix) 245 g/ha PoE <i>fb</i> IC + HW at 40 DAS	13.09	4.41	29.36	15.62	4.26	1.80	2.07	2.71	9.26	3.20	11.23	7.90
Fluzafop-p-butyl + fomesafen (ready-mix) 250 g/ha PoE <i>fb</i> IC + HW at 40 DAS	13.44	3.73	32.95	16.71	4.52	3.12	2.78	3.47	8.83	3.27	11.14	7.75
Propaquizafop + imazethapyr (ready-mix) 125 g/ha PoE <i>fb</i> IC + HW at 40 DAS	15.79	2.45	0.67	6.30	4.04	1.86	2.73	2.88	11.21	3.18	15.50	9.96
Quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha PoE <i>fb</i> IC + HW at 40 DAS	15.33	5.74	6.02	9.03	5.21	2.04	3.08	3.44	9.90	3.30	15.54	9.58
IC <i>fb</i> HW at 20 and 40 DAS	-	4.94	-	1.65	4.27	2.34	3.02	3.21	12.47	3.13	16.68	10.76
Weedy check	87.26	79.29	93.66	86.74	-	-	-	-	-	-	-	-
IC <i>fb</i> HW at 20 and 40 DAS	9.38	4.13	17.68	10.40	10.93	3.63	17.18	10.58	-	-	-	-
Weedy check	-	-	-	-	-	-	-	-	-	-	-	-

Note: Data subjected to $(\sqrt{x+1})$ transformation. Figures in parentheses are means of original values. ; DAS = days after seeding; PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by; IC = inter-cultivation; HW = hand weeding; RM: ready-mix

Table 4. Effect of different treatments on weed management index (WMI) and integrated weed management index (IWMI)

Treatment	Weed management index (WMI)				Integrated weed management index (IWMI)			
	2022	2023	2024	Average	2022	2023	2024	Average
Pendimethalin 750 g/ha PE <i>fb</i> IC + HW at 40 DAS	9.73	4.48	14.26	9.49	11.36	3.98	13.76	9.70
Flumioxazin 125 g/ha PE <i>fb</i> IC + HW at 40 DAS	8.74	4.17	14.19	9.03	10.20	3.67	13.69	9.19
Diclosulam 25.2 g/ha PE <i>fb</i> IC + HW at 40 DAS	7.98	3.94	11.02	7.65	9.23	3.44	10.52	7.73
Oxyfluorfen + pendimethalin (tank-mix) 188+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	6.32	4.07	12.22	7.54	7.24	3.57	11.72	7.51
Diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE <i>fb</i> IC + HW at 40 DAS	7.89	4.49	14.63	9.00	9.12	3.99	14.13	9.08
Pendimethalin + imazethapyr (ready-mix) 800 g/ha PE <i>fb</i> IC + HW at 40 DAS	6.33	4.44	11.33	7.37	7.25	3.94	10.83	7.34
Sodium-acifluorfen + clodinafop-propargyl (ready-mix) 245 g/ha PoE <i>fb</i> IC + HW at 40 DAS	7.10	4.20	12.23	7.84	8.18	3.70	11.73	7.87
Fluazifop-p-butyl + fomesafen (ready-mix) 250 g/ha PoE <i>fb</i> IC + HW at 40 DAS	6.80	4.27	12.14	7.74	7.81	3.77	11.64	7.74
Propaquizafop + imazethapyr (ready-mix) 125 g/ha PoE <i>fb</i> IC + HW at 40 DAS	8.44	4.18	16.50	9.71	9.82	3.68	16.00	9.83
Quizalofop-ethyl + imazethapyr (ready-mix) 90 g/ha PoE <i>fb</i> IC + HW at 40 DAS	7.53	4.30	16.54	9.46	8.72	3.80	16.04	9.52
IC <i>fb</i> HW at 20 and 40 DAS	9.38	4.13	17.68	10.40	10.93	3.63	17.18	10.58
Weedy check	-	-	-	-	-	-	-	-

Note: Data subjected to $(\sqrt{x+1})$ transformation. Figures in parentheses are means of original values. ; DAS = days after seeding; PE = pre-emergence application; PoE = post-emergence application; *fb* = followed by; IC = inter-cultivation; HW = hand weeding; RM: ready-mix

weeding creates a weed-free environment that promotes optimal groundnut growth and development (Mishra 2020). The weedy check had the lowest groundnut pod yield indicating severe impact of unchecked weeds.

Conclusion

Pendimethalin 750 g/ha PE *fb* IC + HW at 40 DAS, diclosulam + pendimethalin (tank-mix) 25.2+500 g/ha PE *fb* IC + HW at 40 DAS and IC *fb* HW at 20 and 40 DAS consistently outperformed than others, offering a balanced and sustainable weed control, higher groundnut pod yield and benefit cost ratio of *Kharif* groundnut.

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RESEARCH ARTICLE

Weed dynamics and soil health in coconut plantations as affected by organic weed management practices

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ABSTRACT

Eco friendly weed management is crucial in sustaining soil health and crop productivity in coconut plantations. A study on the effect of organic practices on weed dynamics and soil health was undertaken in a 20-year-old coconut plantation with a spacing of 7.5 m × 7.5 m. The organic weed management practices tested included: live mulching with *dhaincha* (*Sesbania aculeata*) or horsegram (*Macrotyloma uniflorum*) or cowpea (*Vigna unguiculata*) in the interspaces of coconut trees, intercropping with turmeric (*Curcuma longa*), mulching interspaces of coconut trees using phyto-pharmaceutical waste (byproduct of the ayurveda industry) 20 t/ha, ploughing the interspaces of coconut trees (twice per year). Unploughed interspaces of coconut trees without weeding operations served as check. Weed density and biomass were monitored. Soil samples were periodically analysed for nutrient status and microbial population changes. Grasses were the dominant weeds, followed by broad-leaved weeds. Live mulching and mulching with phyto-pharmaceutical waste resulted in more than 90 % weed control. Mulching with phyto-pharmaceutical waste was free of weeds even after one year of application. Enhanced microbial biomass carbon, dehydrogenase activity, as well as acid phosphatase activity, were observed in plots where intercropping practices or organic waste mulching was practiced. Organic weed management practices not only provided effective weed management but also enhanced soil fertility and microbial activity, making them ideal option for eco-friendly weed management in coconut plantations.

Keywords: Organic mulch, *In-situ* green manuring, Inter-cropping, Soil microbes, Live mulching, Weed shift

INTRODUCTION

Weed management remains a critical factor in sustaining productivity and ecological balance in coconut (*Cocos nucifera* L.) (Remison and Mgbaze 1987), which is the major plantation crop of Kerala. Coconut is generally planted at a spacing of 7.5m × 7.5m and the wider spacing favours greater weed infestation. Weed occurrence is influenced by factors such as crop cover, irrigation, management practices, and light availability (Surekha and Bhat 2025). Except for the initial establishment phase, the direct impact of weed competition on growth and productivity is not a major concern. However, periodic weeding and inter-cultural operations are essential to maintain health of the crop and to facilitate operations such as manuring, irrigation and harvest. There is limited scope for the use of herbicides in a plantation crop like coconut as no registered herbicides with label claim are available. However, being a perennial crop which produces plenty of recyclable plant biomass; there is large scope of adoption of organic farming practices. Coconut-based homestead farming

systems in Kerala are often organic by default. Organic weed management strategies, including green manuring and mulching, not only suppress weed proliferation but also improve soil health, nutrient cycling, and microbial activity, fostering sustainable plantation systems.

Leguminous cover crops play a vital role in sustainable weed management by providing ground cover that suppresses weed germination and growth through light exclusion and competition. Green manures such as *Stizolobium aterrimum* and *Crotalaria* spp. enhance soil fertility by reducing dependence on synthetic inputs, while their decomposition enriches soil organic matter, improves microbial activity, and strengthens soil structure, thereby supporting crop resilience (Servín Niz *et al.* 2023). Horse gram (*Macrotyloma uniflorum*), a pulse crop well adapted to arid and tropical regions, is considered ideal for perennial plantations (Bhardwaj and Yadav 2015). Cowpea (*Vigna unguiculata*) improved physicochemical and biological properties of degraded soils through root exudates that stimulated microbial activity and soil respiration (Farouq *et al.* 2022). Mulching with organic residues, optimal mulch depth, suppress weeds, conserves soil

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moisture, enhances microbial population, and contributes to slow nutrient release (Remison and Mgbeze 1987, Greenly and Rakow 1995). Sun *et al.* (2021) reported that in a 15-year-old *Ligustrum lucidum* forest, a 20-cm organic mulch layer increased bacterial diversity within six months, with community shifts linked to root traits and enzyme activity. Similarly, the use of phyto-pharmaceutical industrial by-products offered cost-effective weed suppression besides the addition of organic matter and micronutrients. Other organic mulching materials such as coffee husk, rice husk, palm leaves, and grasses reduced weeds and improved yield of cucumber (Hutabarat *et al.* 2021). However, information on the performance of such organic weed management practices in coconut plantations under tropical conditions is limited, necessitating the need for detailed evaluation to standardize long-term weed control and productivity enhancement in coconut-based organic farming systems. The objective of this study was to assess the effect of organic effective and ecological option for weed management in coconut plantations so as to sustain soil health and also to study weed flora shifts.

MATERIALS AND METHODS

Two years field study was conducted during 2022 and 2023 in a 20-year-old coconut plantation with a spacing of 7.5 m × 7.5 m. The usual practice of weed management was a single ploughing and basin opening annually during May-June months and there was severe infestation of weeds in between coconut trees rows (interspaces). The field was rainfed and organic manures 25 kg/palm were applied. A randomized block design (RBD) with seven treatments and four replications was used. The tested treatments included T1: *in-situ* green manuring with dhaincha (*Sesbania aculeata*) in the interspaces, T2: *in-situ* green manuring with cowpea (*Vigna unguiculata*) in the interspaces, T3: *in-situ* green manuring with horse gram (*Macrotyloma uniflorum*) in the interspaces, T4: mulching interspaces of coconut trees with phyto-pharmaceutical waste (by-product of the ayurveda industry) 20 t/ha with a thickness of 5-7.5 cm, T5: ploughing twice at 6 months interval in a year, and T6: intercropping with turmeric (*Curcuma longa*). The treatments were imposed after giving a single round of ploughing uniformly. Untreated control without ploughing was maintained as weedy check. All the three green manure crops were sown at a seed rate of 20 kg/ha and the fresh biomass production by the green manure crops range from 2-4 kg/m² at peak vegetative stage. However, they were incorporated

only during the second round of ploughing as green manure addition was not the major objective. Data on weed growth was recorded at 2, 4 and 6 months after sowing of green manure crops/planting of turmeric/mulching with phyto-pharmaceutical waste/ploughing the interspaces. Weed density and biomass was recorded using a quadrat of 0.5m × 0.5m and expressed separately for grasses, sedges and broad-leaved weeds. Soil nutrient status was recorded initially and at the end of experiment. Sowing of green manure crops and planting of turmeric as well as organic waste mulching was done in the month of June in both years. Soil biological properties including microbial biomass carbon, dehydrogenase activity and acid phospho monoesterases, population of fungi, bacteria and actinomycetes were estimated using standard procedures.

RESULTS AND DISCUSSION

Effect on weeds

Weed flora of the experimental area constituted mainly of grasses followed by broad-leaved weeds. Broad-leaved weeds were *Celosia argentea*, *Borreria hispida*, and *Cleome* spp. *Borreria hispida* was dominant. Major grasses were *Megathyrsus maximus* and *Pennisetum pedicellatum*. By the second year, a notable shift in weed flora was observed in the legume-intercropped fields, where broad-leaved weeds gained dominance over grassy weeds. No such shift was recorded in the unweeded check, wherein the first year, at two months, grasses contributed 80% of the total weed biomass, while dicots accounted for only 20% (**Table 1**) and this trend persisted in the second year too, with grasses and dicots contributing 75% and 24%, respectively. However, under different legume intercropping practices, there was a clear ecological shift in weed composition, characterized by a drastic reduction in both the density and biomass of grass weeds. This can be attributed to the suppression of grass weeds due to reduced seed rain, thereby depleting the soil seed bank and weakening their competitive dominance in the weed community. These observations confirm the findings by Davies *et al.* (1997), who reported that annual weeds are unable to establish effectively under dense green manure canopies. The decline in seed production combined with the short seed longevity of many annual grasses accelerated this shift (Bohan *et al.* 2011). Leguminous green manures have been shown to reduce the weed seed bank by up to 65%, with residual effects persisting even up to three years (Melander *et al.* 2020). Thus, cover cropping with

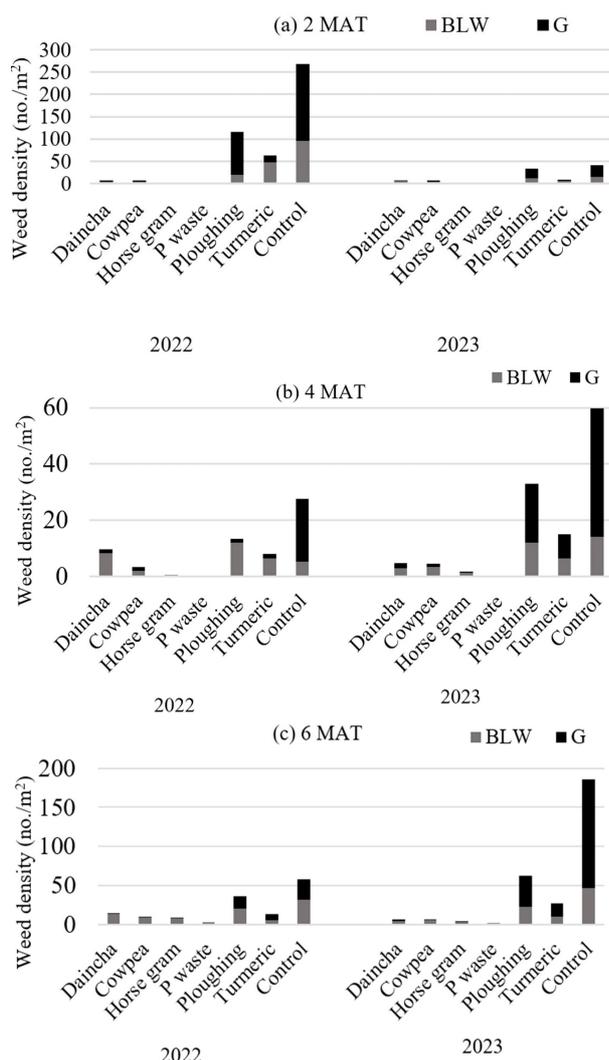


Figure 1. Weed density at (a) 2 months after treatment application (MAT), (b) 4 months after treatment application, (c) 6 months after treatment application

green manure crops play a pivotal role in both weed suppression and seed bank depletion, contributing significantly to ecological weed management in organic or natural farming systems.

A comparison of weed density in different treatments showed (Figure 1) that in the treatments *in-situ* green manuring using horse gram and mulching with phytopharmaceutical waste, no weeds were present at two months after treatment (MAT). In plots intercropped with turmeric, the weed density was very high compared to the legume intercropped plots as smothering effect was less compared to legumes (Figure 1a). The significantly highest weed density was recorded from unweeded control, followed by ploughing alone. However, ploughing could considerably reduce (by 43%) the weed density compared to weedy check. The same trend was noticed at 4 months (Figure 1b). By 6 months,

broad-leaved weeds constituted the major flora (Figure 1c). However, scarcity of rainfall caused declining trend of weed density.

In general, a sharp decline in total weed density was observed during the second year at two months and showed an increasing trend by 4 and 6 months due to favourable climatic factors (Figure 1). The observed decline in weed density at two months during the second year can be attributed to residual effects of earlier practices and reduced initial weed emergence. However, the increasing weed density by four and six months suggests that limited soil disturbance may allow some late-emerging weed species to establish, especially under favourable climatic conditions. In such systems, legume intercropping serve as a biologically integrated weed suppression strategy. The dense canopy and competitive nature of legumes help smother weeds and reduce their light and space resources. The population of broad-leaved weeds was higher compared to grasses. The same trend as in the first year was followed in all the treatments. Ploughing of interspaces proved less effective than intercropping, confirming that mechanical weeding alone is not sufficient to control diverse weed flora. But, mechanical weeding was statistically superior than the unweeded check. When done occasionally, it can be an effective and low-cost option in coconut plantations, where wide interspaces are available and weeds have little impact on yield if the basin area around the palms is kept weed-free. The 60% and 40% reduction in weed density by six months in 2022 and 2023 respectively, highlights the cumulative benefits of integrating tillage with cover cropping.

During both years weed biomass was recorded at two-month intervals and the same trend as that of weed density was observed. At 2 MAT, *in-situ* green manuring with horsegram and mulching with phytopharmaceutical waste were most effective with 100% weed control (Table 1). *In-situ* green manuring with cowpea and dhaincha showed a weed biomass reduction of 95%, compared to unweeded control and were statistically comparable. In intercropping with turmeric, 82% reduction in weed biomass was observed. The highest weed biomass was recorded from the unweeded control, followed by ploughing alone. At 4 and 6 MAT also, a similar trend was noticed (Table 1). By six months, weed biomass increased. In all legume intercropping treatments, weed biomass was statistically comparable, and on average, the reduction in weed biomass was 96% over the unweeded control, indicating the effectiveness of cover cropping.

From both ecological and practical farming perspectives, green manuring and mulching clearly outperformed ploughing in managing weeds in coconut plantations. Legume intercropping sustained a weed control efficiency (WCE) of over 90% up to six months (**Figure 2**), offering ecological benefits such as improved soil fertility through nitrogen

fixation, suppression of weed seed germination and reducing weed seed bank. Mulching with phyto-pharmaceutical waste provided even more immediate suppression, achieving 100% WCE at two and four months, and 98% at six months, by acting as a physical barrier to weed emergence while also conserving soil moisture and enhancing microbial

Table 1. Weed biomass at 2, 4, and 6 months after treatment application

Treatment	2022			2023		
	BLW	G	Total	BLW	G	Total
<i>Weed biomass (g/m²) at 2 months after treatment</i>						
<i>In-situ</i> green manuring with dhaincha in the interspaces of coconut trees (interspaces)	1.85 ^d (2.94)	1.78 ^d (2.67)	2.47 ^d (5.61)	3.17 ^c (9.67)	1.93 ^d (3.33)	3.66 ^d (13.00)
<i>In-situ</i> green manuring with cowpea in the interspaces	2.02 ^d (3.60)	1.37 ^{de} (1.37)	2.34 ^d (4.97)	2.46 ^{cd} (5.67)	1.54 ^{de} (2.33)	2.91 ^d (8.00)
<i>In-situ</i> green manuring with horse gram in the interspaces	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)	1.54 ^{de} (2.33)	0.71 ^e (0.00)	1.54 ^e (2.33)
Mulching interspaces using phytopharmaceutical waste 20 t/ha	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)
Ploughing twice in the interspaces	7.36 ^b (53.61)	13.96 ^b (194.62)	15.77 ^b (248.23)	6.84 ^a (46.33)	11.74 ^b (137.67)	13.57 ^b (184.00)
Inter cropping with turmeric in the interspaces	6.47 ^c (41.39)	3.93 ^c (14.98)	7.54 ^c (56.37)	5.66 ^b (32.00)	5.89 ^c (34.33)	8.17 ^c (66.33)
Unweeded control	8.55 ^a (72.61)	16.89 ^a (284.64)	18.91 ^a (357.25)	7.72 ^a (59.33)	13.52 ^a (182.67)	15.55 ^a (242.00)
LSD (p=0.05)	0.43	0.83	0.92	0.987	1.093	1.071
<i>Weed biomass (g/m²) at 4 months after treatment</i>						
<i>In-situ</i> green manuring with dhaincha in the interspaces of coconut trees (interspaces)	5.47 ^a (29.42)	1.00 ^b (0.50)	5.52 ^c (29.92)	3.76 ^c (13.67)	2.21 ^d (4.67)	4.33 ^d (18.33)
<i>In-situ</i> green manuring with cowpea in the interspaces	3.97 ^b (15.28)	1.16 ^b (0.85)	4.08 ^d (16.13)	3.69 ^c (13.33)	1.79 ^{de} (3.33)	4.14 ^d (16.67)
<i>In-situ</i> green manuring with horse gram in the interspaces	1.17 ^c (0.88)	0.71 ^b (0.00)	1.17 ^e (0.88)	2.88 ^d (8.00)	1.09 ^{ef} (1.00)	3.02 ^e (9.00)
Mulching interspaces using phytopharmaceutical waste 20 t/ha	0.71 ^c (0.00)	0.71 ^b (0.00)	0.71 ^e (0.00)	0.71 ^e (0.00)	0.71 ^f (0.00)	0.71 ^f (0.00)
Ploughing twice in the interspaces	3.56 ^b (12.17)	7.60 ^a (57.26)	8.36 ^b (69.43)	9.69 ^a (93.67)	14.19 ^b (201.00)	17.17 ^b (294.67)
Inter cropping with turmeric in the interspaces	2.06 ^c (3.73)	3.13 (12.30)	4.02 ^c (16.03)	6.46 ^b (41.33)	8.47 ^c (71.33)	10.64 ^c (112.67)
Unweeded control	3.89 ^b (14.66)	8.73 ^a (75.66)	9.53 ^a (90.33)	10.46 ^a (109.00)	18.82 ^a (354.00)	21.51 ^a (463.00)
LSD (p=0.05)	1.23	1.42	1.78	0.773	0.990	0.955
<i>Weed biomass (g/m²) at 6 months after treatment</i>						
<i>In-situ</i> green manuring with dhaincha in the interspaces of coconut trees (interspaces)	5.12 ^c (26.33)	0.95 ^d (0.43)	5.16 ^d (26.77)	4.44 ^c (20.00)	2.00 ^d (3.67)	4.83 ^d (23.67)
<i>In-situ</i> green manuring with cowpea in the interspaces	4.72 ^{cd} (22.33)	0.82 ^d (0.20)	4.74 ^d (22.53)	4.39 ^c (19.33)	1.83 ^{de} (3.67)	4.77 ^d (23.00)
<i>In-situ</i> green manuring with horse gram in the interspaces	4.28 ^d (18.33)	0.85 ^d (0.23)	4.30 ^d (18.57)	4.35 ^c (19.00)	1.54 ^{de} (2.33)	4.59 ^d (21.33)
Mulching interspaces using phytopharmaceutical waste 20 t/ha	2.49 ^e (6.33)	0.71 ^d (0.00)	2.49 ^e (6.33)	2.60 ^d (7.00)	0.71 ^e (0.00)	2.60 ^e (7.00)
Ploughing twice in the interspaces	6.42 ^b (41.33)	11.56 ^b (133.33)	13.21 ^b (174.67)	9.59 ^a (92.00)	14.77 ^b (218.33)	17.61 ^b (310.33)
Inter cropping with turmeric in the interspaces	3.21 ^e (10.33)	9.40 ^c (88.00)	9.91 ^c (98.33)	6.96 ^b (48.67)	11.03 ^c (122.00)	13.05 ^c (170.67)
Unweeded control	7.78 ^a (60.67)	14.42 ^a (208.00)	16.38 ^a (268.67)	8.99 ^a (81.00)	21.91 ^a (479.67)	23.67 ^a (560.67)
LSD (p=0.05)	0.722	0.747	0.928	0.893	1.198	1.054

$\sqrt{x+0.5}$ transformed values, original values in parenthesis. *BLW – broad-leaved weeds, G - grasses.

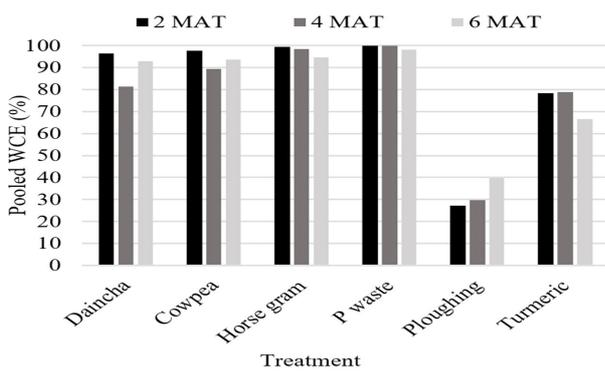


Figure 2. Effect of weed management practices on weed control efficiency (WCE)

Dhaincha - in-situ green manuring with dhaincha in the interspaces; Cowpea - in-situ green manuring with cowpea in the interspaces; Horse gram - in-situ green manuring with horse gram in the interspaces; P waste - mulching interspaces of coconut trees using phyto-pharmaceutical waste 20 t/ha; Ploughing - ploughing twice; Turmeric - intercropping with turmeric; Control - weedy check

activity. For farmers, these practices reduce the need for frequent weeding, save labour costs, and improve soil health-leading to better long-term productivity.

Soil chemical analysis

Soil samples were collected before and after the experiment. The primary nutrient status of the soil was N (86 kg/ha), P (52 kg/ha) and K (232 kg/ha). After the application of the treatments, pH of the soil varied from 5 to 5.99 and EC varied from 30 to 110 μS/m. The highest pH and EC were registered in phytopharmaceutical waste mulched field (Figure 3). The total organic matter, as well as organic carbon content, were higher in legume intercropping as well as organic waste mulching compared to ploughing alone and unweeded control. The organic matter content was higher in green manuring with horse gram and mulching with phytopharmaceutical waste with about 4% increase over unweeded check.

The organic interventions resulted in noticeable increase in soil carbon status. Both total organic matter (OM) and organic carbon (OC) were higher in the legume-intercropped and mulched plots compared to ploughed and unweeded controls (Figure 3). Green manuring with horse gram and mulching with phytopharmaceutical waste each

showed increase in organic matter from initial value of 8% to 10% and 12% respectively over the control, suggesting effective carbon input and nutrient recycling through leumes biomass incorporation and decomposition confirming the findings of Montanaro *et al.* (2017); Chahal *et al.* (2020).

Iron (Fe), the most abundant redox-active metal in the Earth’s crust, cycles between Fe(III) and Fe(II) through microbial and chemical processes. It plays an important role in deciding rhizosphere microbial communities, with previous studies showing that iron availability can influence microbial composition more than many other nutrients. Continuous cropping has been associated with a decline in bacteria involved in iron respiration—microorganisms that convert plant-unavailable Fe(III) into Fe(II), which roots can absorb (Yang *et al.* 2025). Continuous cropping or high organic matter can immobilize Fe through complexation, indirectly affecting actinomycete population by altering nutrient availability and redox conditions (Peng *et al.* 2022). The observed reduction in soil iron content (Figure 4) can be linked to a decline in actinomycete population, as these microorganisms contribute to iron cycling through the production of siderophores that mobilize Fe(III) into plant-available forms; Reduced actinomycete population under continuous cropping could therefore limit iron solubilization, accelerating the depletion of available iron in the soil. In contrast, manganese levels remained relatively stable, likely due to its higher mobility in soil compared to iron.

Soil microbiological analysis

Enhanced microbial biomass carbon, dehydrogenase activity, as well as acid phosphatase activity, were observed in plots where intercropping practices or phytopharmaceutical waste application were followed (Figure 5). Also, in the second year of treatment application, a remarkable increase in these parameters could be observed indicating improvement in soil health. A marked increase in the population of fungi and bacteria was observed in

Table 2. Soil nutrient status of coconut plantations as affected by phytopharmaceutical waste application and green manure crops cultivation in the interspaces of coconut trees

Phytopharmaceutical waste	N (%)	P (%)	K (%)	Micronutrient (ppm)		Heavy metals (ppm)				Phenol content (%)
				Cu	Fe	Ni	Cr	Cd	Pb	
Phytopharmaceutical waste (fresh)	1.66	0.151	0.331	3.7	406	84.04	54.3	BDL	276	0.083
Phytopharmaceutical waste (decomposed - 6 months after soil application)	1.05	0.162	0.149	1.9	111.6	7.70	29.8	BDL	181	0.025
Green manure crops		N (%)			P (%)					K (%)
Cowpea		3.0			0.45					1.4
Horse gram		3.0			0.42					1.4
Dhaincha		3.5			0.60					1.2

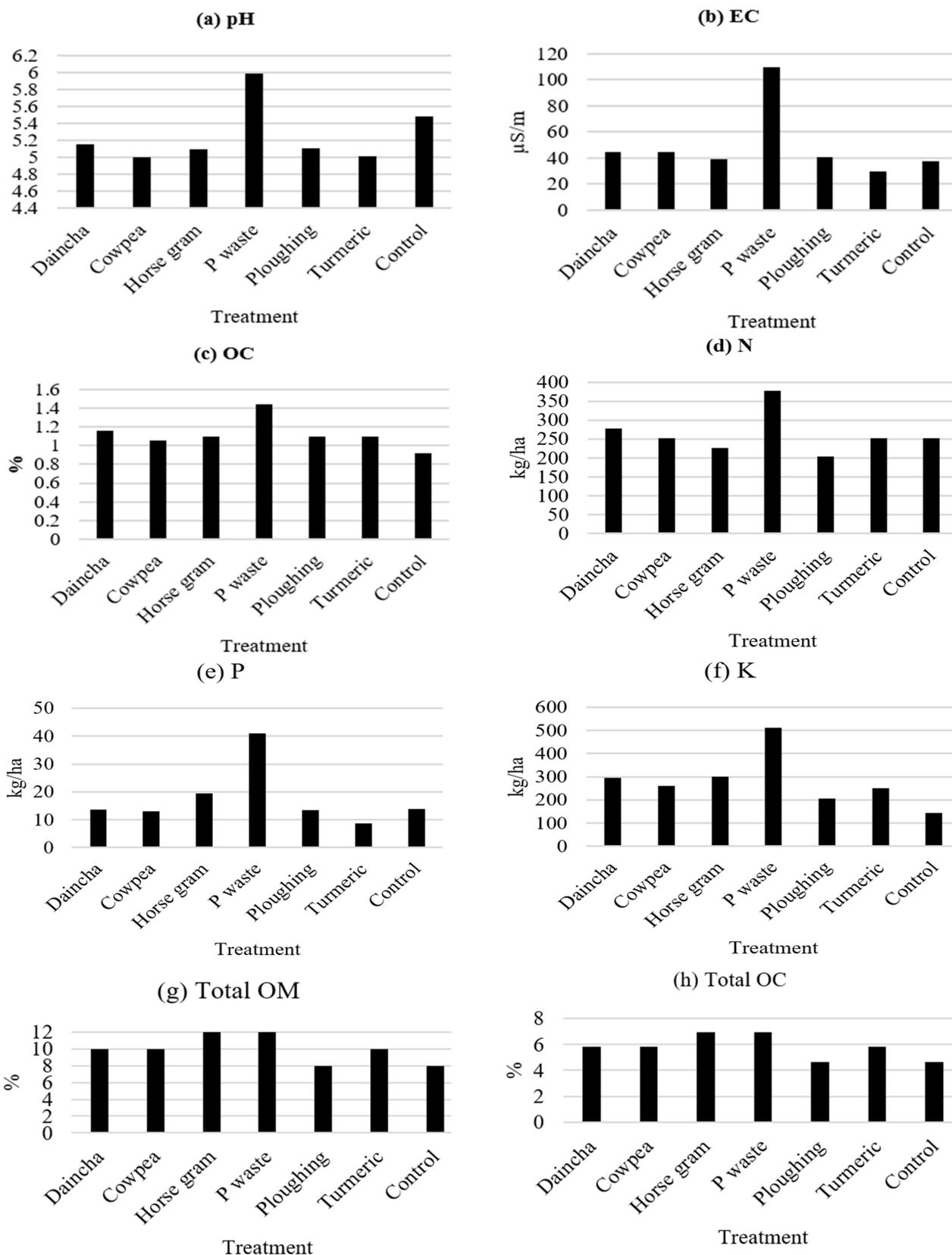


Figure 3. Soil chemical parameters (a) pH, (b) EC, (c) Organic carbon, (d) Nitrogen (N), (e), Phosphorus (P), (f) Potassium (K), (g) Total organic matter (%), (h) Total Organic carbon (%) as affected by tested treatments

Daincha - in-situ green manuring with dhaincha in the interspaces; Cowpea - in-situ green manuring with cowpea in the interspaces; Horse gram - in-situ green manuring with horse gram in the interspaces; P waste - mulching interspaces of coconut trees using phyto-pharmaceutical waste 20 t/ha; Ploughing - ploughing twice; Turmeric - intercropping with turmeric; Control – weedy check

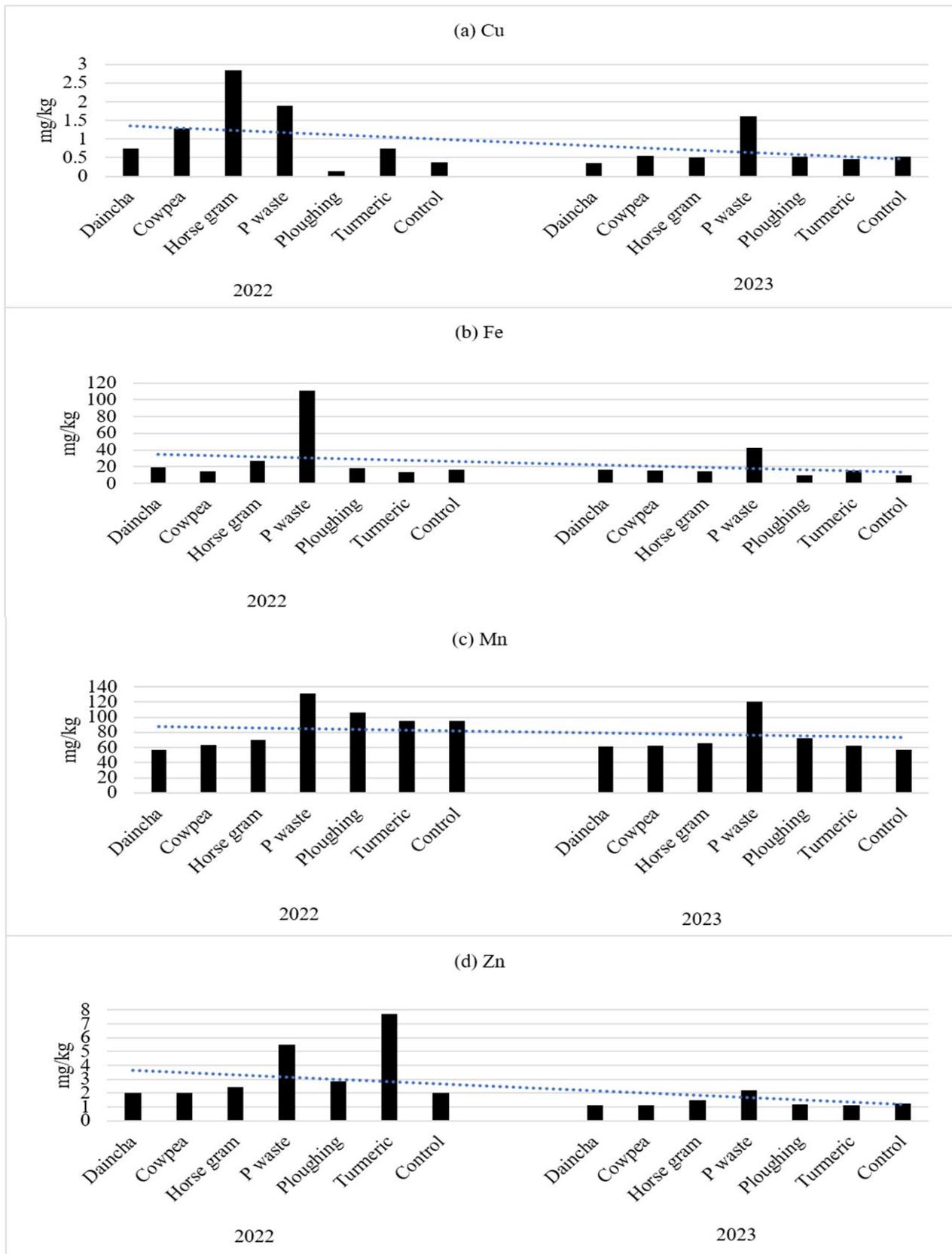


Figure 4. Soil micro-nutrient status (a) Cu, (b) Fe, (c) Mn, (d) Zn as affected by tested treatments

Dhaincha - in-situ green manuring with dhaincha in the interspaces; Cowpea - in-situ green manuring with cowpea in the interspaces; Horse gram - in-situ green manuring with horse gram in the interspaces; P waste - mulching interspaces of coconut trees using phyto-pharmaceutical waste 20 t/ha; Ploughing - ploughing twice; Turmeric - intercropping with turmeric; Control – weedy check

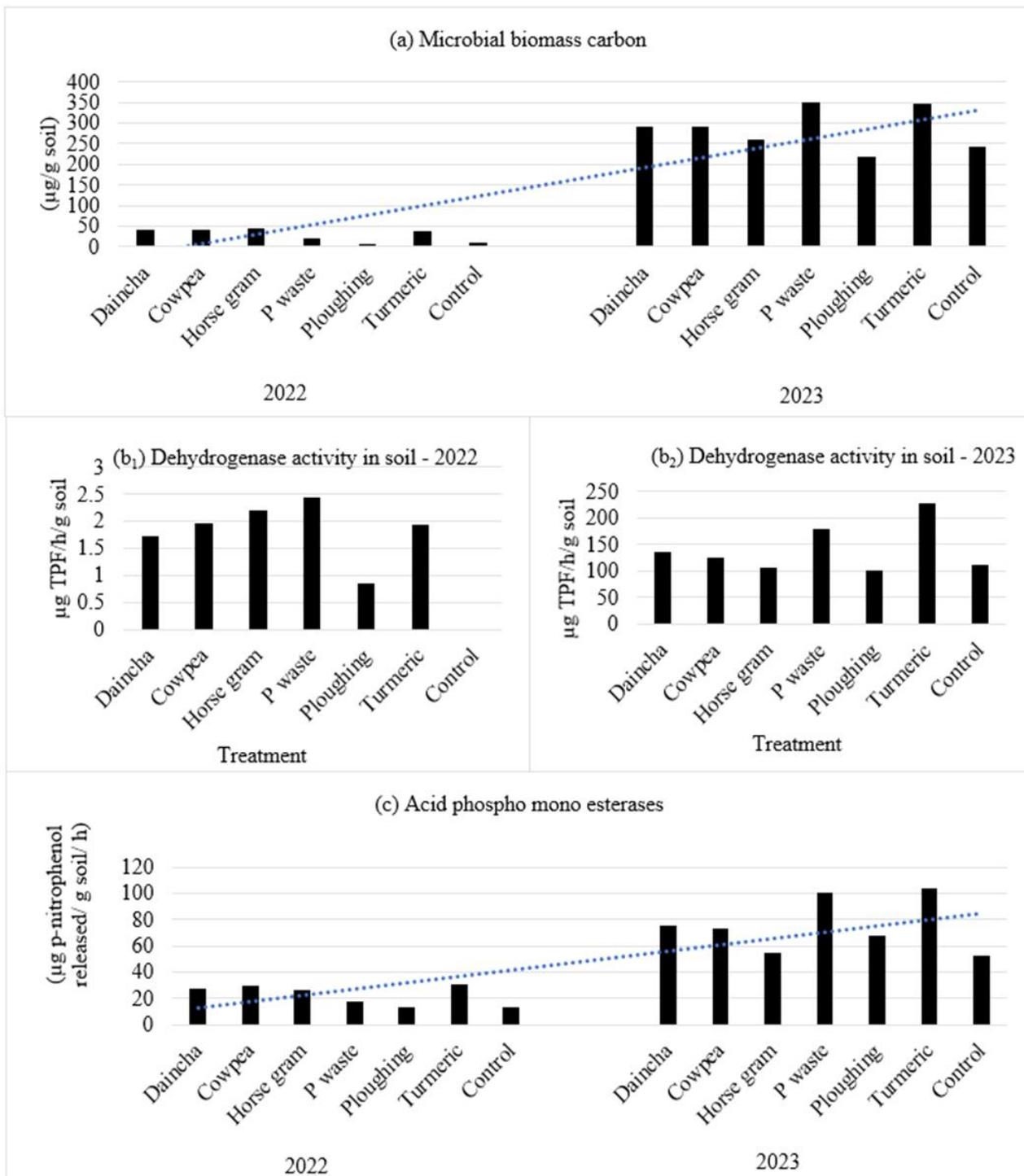


Figure 5. Soil microbiological analysis (a) Microbial biomass carbon, (b) Dehydrogenase activity, (c) Acid phospho mono esterases as affected by treatments

Dhaincha – in-situ green manuring with dhaincha in the interspaces; Cowpea – in-situ green manuring with cowpea in the interspaces; Horse gram – in-situ green manuring with horse gram in the interspaces; P waste - mulching interspaces of coconut trees using phytopharmaceutical waste 20 t/ha; Ploughing – ploughing twice, Turmeric – intercropping with turmeric; Control- weedy check

legume intercropped and organic mulched plots (Figure 6). Fungi dominated the microbial population, followed by bacteria. Actinomycetes population was lower and no definite trend could be observed with treatments. These results highlight

how legume intercropping and mulching improve soil health by creating a microbiologically active and resilient soil ecosystem, which is essential for nutrient cycling, disease suppression, and long-term soil fertility.

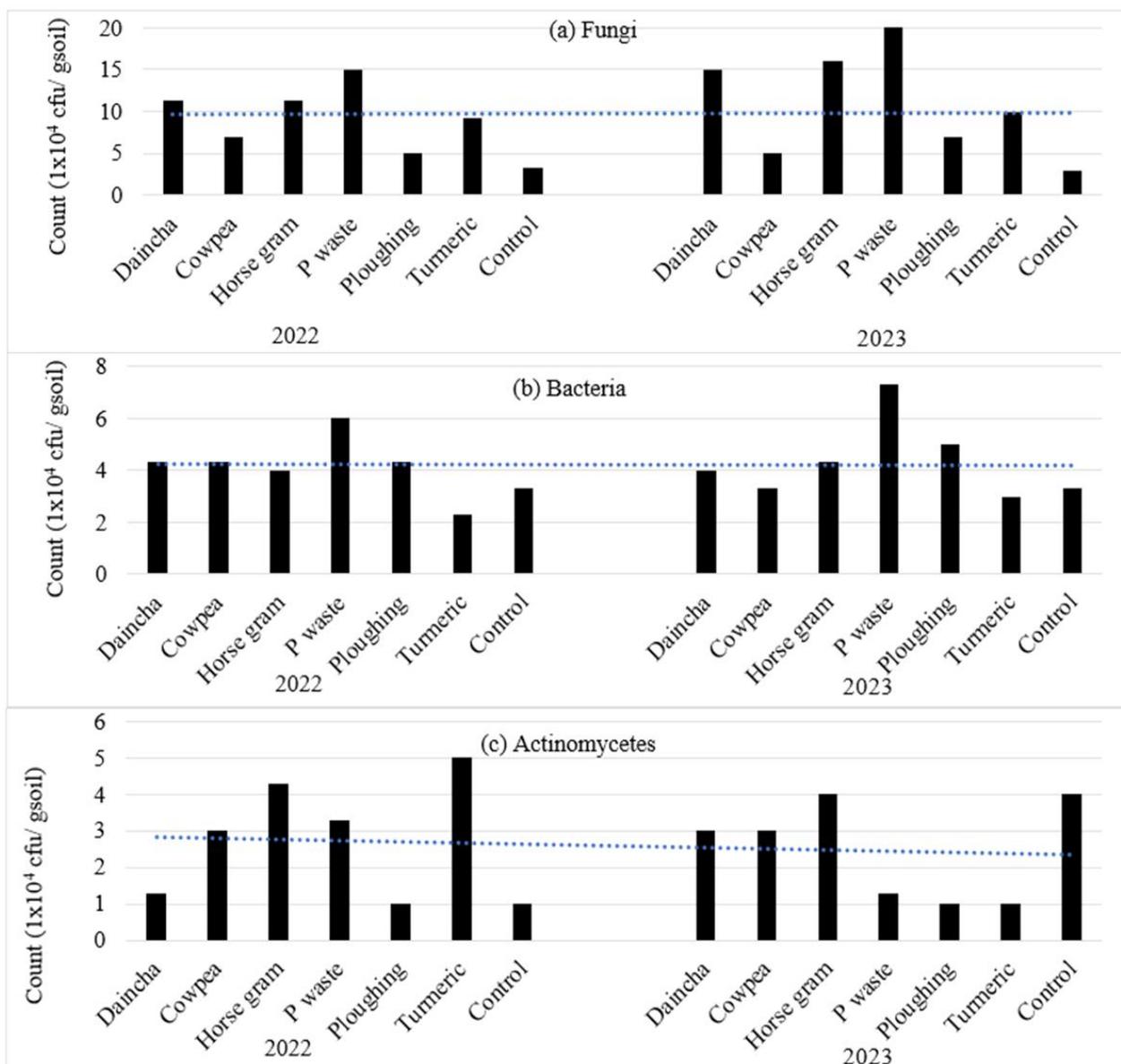


Figure 6. Soil microbial count (1x10⁴ cfu/g soil) (a) Fungi, (b) Bacteria, (c) Actinomycetes as affected by treatments Dhaincha - in-situ green manuring with dhaincha in the interspaces; Cowpea - in-situ green manuring with cowpea in the interspaces; Horse gram - in-situ green manuring with horse gram in the interspaces; P waste - mulching interspaces of coconut trees using phyto-pharmaceutical waste 20 t/ha; Ploughing - ploughing twice; Turmeric - intercropping with turmeric; Control – weedy check

The organic weed management practices—particularly *in-situ* green manuring and mulching with phyto-pharmaceutical waste offer significant agronomic and ecological benefits. Apart from effective and sustained weed suppression these substantially improved soil organic carbon, microbial activity, and overall soil health in coconut plantations. Enhanced microbial biomass and enzymatic activities, along with greater fungal and bacterial populations, indicate a more resilient and biologically active soil ecosystem.

A noticeable weed shift was observed in mulched and legume intercropped plots, where

broad-leaved weeds began to dominate over grasses, indicating a shift in weed flora composition due to reduced seed rain from grasses, altered soil conditions, and competition from leguminous cover. For natural farming conditions, legume intercropping proved particularly valuable in improving nutrient cycling and weed suppression, reinforcing the effectiveness of biodiversity-based, low-input strategies over conventional mechanical methods like ploughing. Overall, the findings of this study highlight the potential of integrated organic weed management approaches to manage weeds, promote soil health, and support long-term sustainability in perennial cropping systems of coconut.

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RESEARCH ARTICLE

Plant specific responses of *Imperata cylindrica* leaves extracts (in-vitro) on selected forest tree species

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ABSTRACT

Imperata cylindrica, a widespread invasive weed, is significantly disrupting plantations and degraded hill forests in Bangladesh through the release of allelopathic chemicals that inhibit the growth of other plants. To assess its allelopathic impact, an experiment was conducted using six concentrations of *Imperata cylindrica* leaves extract (prepared at 28–30°C) to evaluate effects on seed germination and seedling growth of four forest tree species: *Syzygium fruticosum* (Putijam), *Albizia procera* (Silkeroi), *Azadirachta indica* (Neem), and *Ficus hispida* (Dumur). The extracts' lower concentrations (<20 g/L) stimulated germination in *S. fruticosum* and *A. indica*, while concentrations above 20 g/L inhibited germination of all species. Increasing concentrations negatively affected shoot growth, particularly of *F. hispida*, and root growth of *A. indica*. Among the tested species, *A. procera* showed the highest vigor index for both root and shoot growth at the 50 g/L concentration, indicating a higher tolerance to *I. cylindrica* allelopathy. In contrast, *F. hispida* was the most adversely affected. These findings suggest that *A. indica* and *A. procera* are more resilient to the allelopathic effects of *I. cylindrica* and could be promising candidates for reforestation or afforestation in areas heavily infested with *Imperata cylindrica*. However, greenhouse studies and field studies are needed for drawing definitive conclusions.

Keywords: Allelopathy, *Albizia procera*, *Azadirachta indica*, *Imperata cylindrica*, Invasive weed, Forest trees

INTRODUCTION

Allelopathy is one of the well-known mechanisms by which interactions between organisms detrimentally influence the structure and functions of ecosystems (Powell *et al.* 2013). A species will be deemed invasive when it expands beyond its normal range and has the potential to affect the native variety, ecosystem structure, and general function (Thiébaud *et al.* 2019). Multiple studies have demonstrated evidence of detrimental allelopathic effects on germination, growth, development, survival, reproduction, nitrogen fixation, and/or selective mycorrhizal fungi by the release of allelochemicals via leaching, decomposition of litter, exudation of roots, and/or direct volatilization (Kundra *et al.* 2023, Schulz and Tabaglio 2025) though these interactions vary species to species, dose to dose, and under different weather conditions.

Imperata cylindrica (L.) P. Beauv. also known as cogon grass, japgrass, blady grass, sungrass, speargrass, alang-alang, and lalang-alang, is a C4 rhizomatous perennial weed under Poaceae family with culms that grow upright to ascending and

normally reach heights of 1.2m but can reach heights of 3 m (Holm *et al.* 1977, MacDonald 2004). This species is recognized as one of the top ten most notorious invasive weeds among the world's 100 worst invasive alien species, noted for its significant disruptive impact across diverse ecosystems (Kato-Noguchi 2022) that harms the ecosystem and causes significant economic loss in both natural and agricultural settings. Like globally, *I. cylindrica* shows its invasiveness by growing abundantly in the hills (Kato-Noguchi 2022, Mukul *et al.* 2021), and can hamper or even destroy the growth of different natural vegetation. *I. cylindrica* has a high phenotypic plasticity, which means it can do well in a wide range of conditions (MacDonald 2004, Bryson *et al.* 2010). Invasive plants have phytotoxic chemical substances that disrupt the physiological and biochemical processes of other plants. 72 chemical components have been extracted and identified from *I. cylindrica* including the main constituents are saponins, flavonoids, phenols, and glycosides (Jung and Shin 2021). All those available phytochemicals in *Imperata cylindrica* are also found in some other species that show negative impact on its surrounding species in forest and agroforestry ecosystems. Invasive alien species are a major factor in the reduction of biodiversity. As the species invade hills and there is a

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high possibility that it might have some impact on the hill forest vegetation. However, this impact has not been assessed yet in the climatic conditions of Bangladesh. Moreover, *Imperata cylindrica*'s allelopathic inhibition/stimulation effects on hill tree species was not studied. Therefore, a study was conducted to quantify the impact of the leaves extracts of *I. cylindrica* on seed germination and initial growth of four common trees under in-vitro conditions.

MATERIALS AND METHODS

The study was conducted at the Society and Environment Research Lab of the Institute of Forestry and Environmental Sciences, University of Chittagong (IFESCU) from May to October 2024.

Imperata cylindrica was selected as the donor species due to its ecological characteristics, while selected receptor species include *Syzygium fruticosum* (Putijam), *Albizia procera* (Silkoro), *Azadirachta indica* (Neem), and *Ficus hispida* (Dumur). The selection of receptor species was guided by the natural availability of mature seeds during the study period and their typical occurrence within the hill forest ecosystems of the Chattogram region.

Fresh and mature *Imperata cylindrica* leaves were gathered from various hill slopes within the University of Chittagong campus. The collected leaves were initially air-dried under ambient conditions to reduce moisture content. Following drying, the leaves were chopped into uniform fragments ranging from 0.5 to 1 cm in length to facilitate efficient extraction of phytochemicals. To assess the potential allelopathic effects (inhibitory or stimulatory) of *Imperata cylindrica* leaf extracts, six concentrations were prepared using 10 g, 20 g, 30 g, 40 g, 50 g, and 100 g of chopped leaf material soaked in 1 L of distilled water and maintained at a temperature between 28°C-32°C for 24 hours. Afterwards the mixtures were filtered through four layers of cheesecloth to remove solid residues. The

resulting aqueous extracts were adjusted to final concentrations of 10 g/L, 20 g/L, 30 g/L, 40 g/L, 50 g/L, and 100 g/L, and subsequently stored under appropriate conditions for use in seed treatment experiments. The treatments included the 20 seeds of receptor plants grown each in 0 g/L (Control *i.e.* distilled water), 10 g/L, 20 g/L, 30 g/L, 40 g/L, 50 g/L, and 100 g/L concentration to study the germination and growth test in-vitro using a 12 cm long sterile petri dish covered with Whatman No. 3 filter paper at room temperature. The Petri-dishes were sterilized by maintaining a temperature of 200 degree Celsius. The experimental setup followed a randomized complete block design (RCBD) replicated thrice. Each day, a small amount of the extract from each concentration was applied to each petri dish of the corresponding treatment, just enough to moisten the seeds, whereas the control was applied only with distilled water. To accommodate the final germination rate and the determination of the shoot and root lengths, the experiment was expanded beyond a period of 30 day.

Analysis of Variance (ANOVA) and Duncan's Multiple Range Test were conducted to evaluate the receptor species' percentage of seed germination (%), height of the root (cm), shoot length (cm), and vigor index of the root and shoot collected throughout the experiment (Table 1).

RESULTS AND DISCUSSION

Seed germination (%) of receptor tree species

The seed germination (%) of the four receptor tree species decreased with the increasing concentrations of the *I. cylindrica* extracts (Figure 1). Both the stimulating and inhibiting effects on the germination of receptor species seeds was observed with different concentrations of *I. cylindrica* leaves extracts. Significant inhibiting effects on the seed germination of *Syzygium fruticosum* (100 g/L concentration compared to 10 g/L concentration) and *Ficus hispida* (100 g/L concentration compared to 40 g/L concentration) were recorded. Conversely, there was also a significant stimulating effect on the seed germination of *Azadirachta indica* at 20 g/L

Table 1. The formulae used during the calculations

Variable	Equation	Reference
Germination Percentage, G	$\frac{\text{Number of seeds germinated}}{\text{Total Number of seeds sown}} \times 100$	Alemu <i>et al.</i> 2016
Vigor Index, V	Germination percentage x seedling length	Abdul-Baki and Anderson 1973
Inhibition, I	$100 - (E_2 \times 100/E_1)$	Surendra and Pota 1978

[I = % inhibition; E1 = The response of the control plant; E2 = The response of the treatment plant]

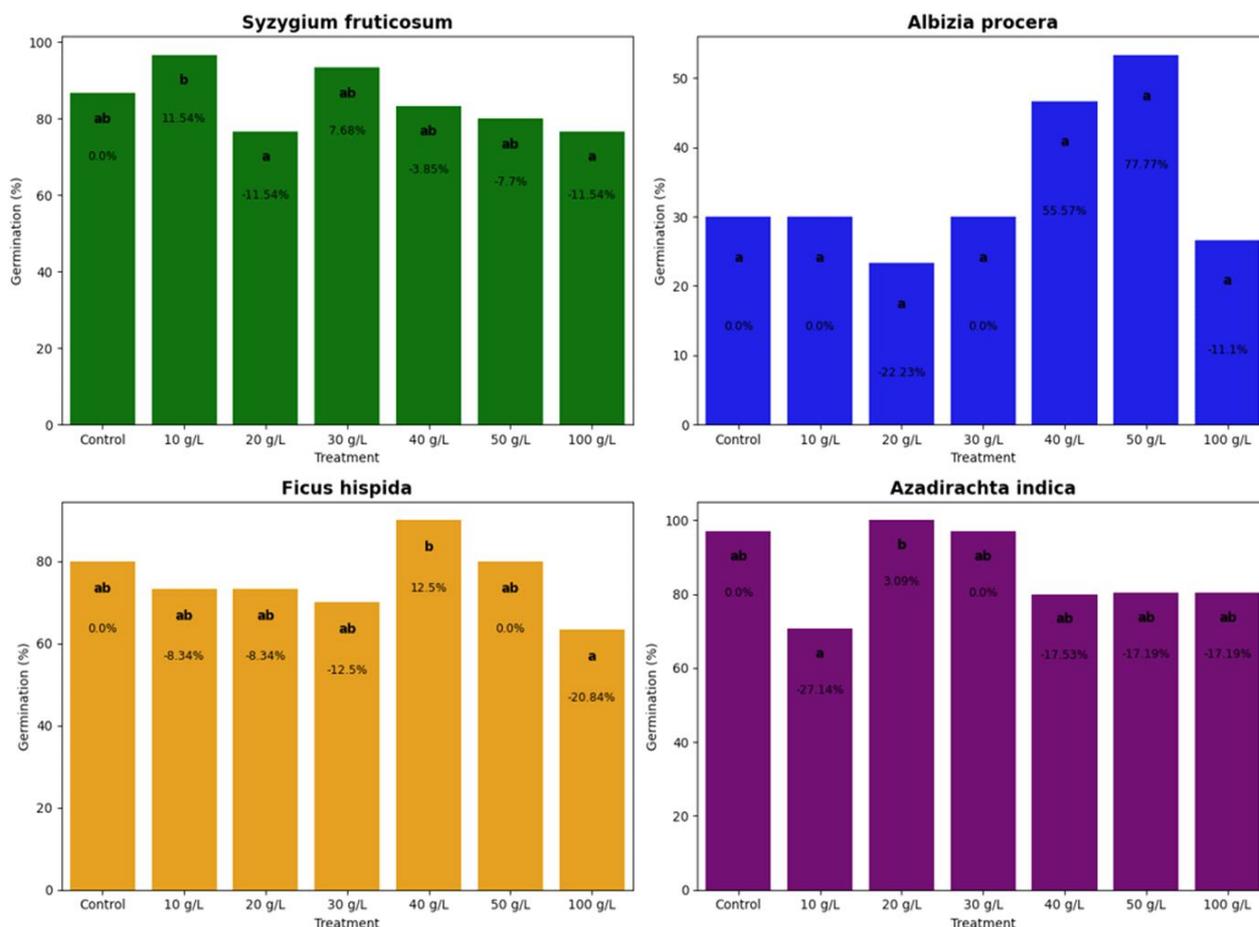


Figure 1. The receptor trees seed germination percentage and inhibition/stimulation by different leaves extract concentrations of *Imperata cylindrica*

concentration compared to 10 g/L (Figure 1).

The highest seed germination (%) with little stimulation at low concentrations was observed in *Azadirachta indica* with 20 g/L and *Syzygium fruticosum* with 10 g/L concentration. Possibly, a lower concentration of the leachate may induce little stress (Subtain *et al.* 2014) that does not significantly affect the germination percentage of the recipient crops, alternatively, leaf with a lower concentration of leachate can serve as an accelerator to enhance germination (Pedrol *et al.* 2006) regarding few instances demonstrating the stimulating effects in *Syzygium fruticosum* and *Azadirachta indica*. For *Ficus hispida*, the inhibition percentage increased with the high concentration of the treatment which was also revealed elsewhere (Moro Cordobés *et al.* 2023) and (Suzuki *et al.* 2018). Except for *Albizia procera*, most species showed seed germination inhibition when treated with higher concentrations. This type of inhibiting germination may result due to the presence of benzoic acids (Hagan *et al.* 2013).

Root and Shoot elongation of receptor tree species

The seed germination test was expanded beyond 30 days to observe the growth of roots and shoots of the receptor seeds. Varying inhibiting growth of roots of different receptor species was observed due to increased concentrations of *Imperata cylindrica* leaves extracts. *Azadirachta indica* showed highest root growth (4.62 cm in 30 g/L concentration) compared to other receptor species in control condition, whereas *Albizia procera* showed highest shoot growth (7.26 cm in 30 g/L concentration) followed by *Azadirachta indica* (4.19 cm in 50 g/L concentration) and *Syzygium fruticosum* (3.53 cm in 100 g/L concentration) under control condition. Significant stimulation in root elongation was observed in *Albizia procera* at 30 g/L concentration compared to 10 g/L, whereas *Azadirachta indica* at 50 g/L concentration compared to the rest. *Syzygium fruticosum* at 100 g/L concentration compared to 30 g/L showed a gradual stimulation in shoot growth as the concentration increased. *Syzygium fruticosum* (100 g/L concentration compared to 20 g/L concentration), and *Ficus hispida* (100 g/L concentration compared to 10 g/L concentration) showed significant inhibiting root growth due to

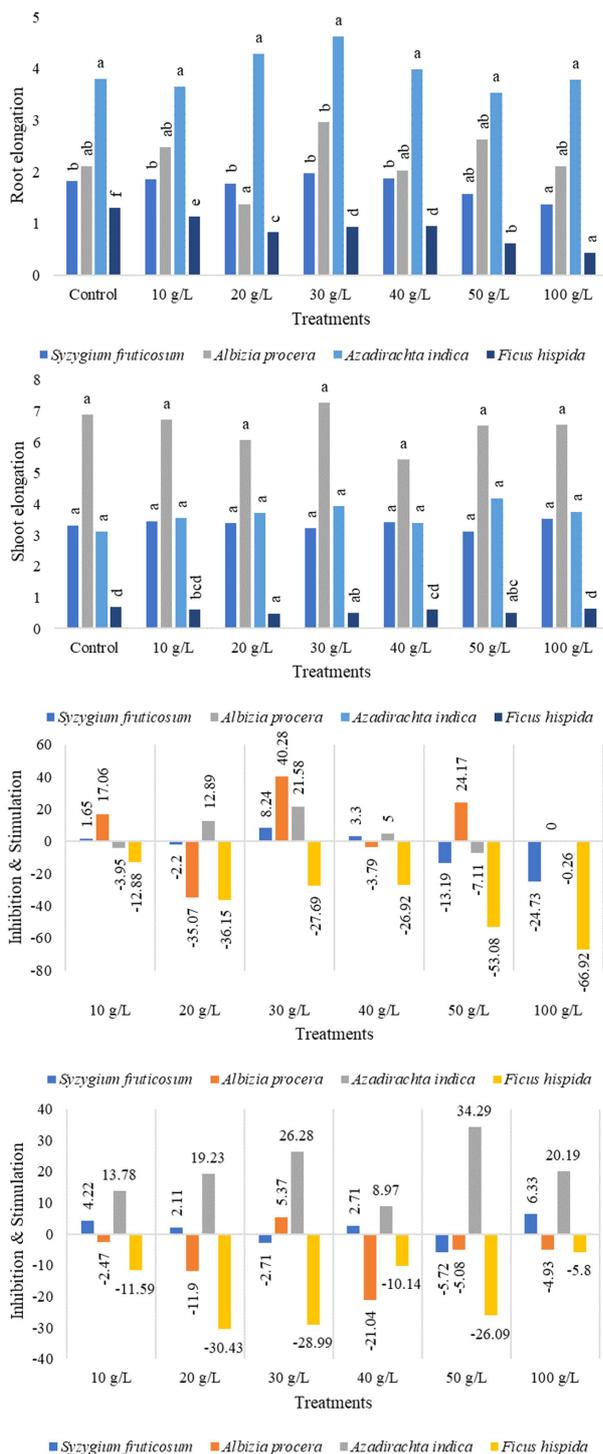


Figure 2. Root elongation (cm) and shoot elongation (cm) of receptor tree species and inhibition and stimulation of root and shoot in different concentrations on *Imperata cylindrica* leaves extracts

increased concentration of *I. cylindrica* extracts. The maximum root inhibition of *Ficus hispida* (67%) followed by *Syzygium fruticosum* (25%) was recorded. On the other hand, highest shoot inhibiting growth of *Ficus hispida* (30%) followed by *Syzygium*

fruticosum (6%) was observed with different concentrations of *I. cylindrica* leaves extracts (Figure 2).

Root vigor index of receptor tree species

The control exhibits a significantly greater vigor index value for *Ficus hispida* (104 in Control compared to 28 in 100 g/L concentration) and a lower vigor index value for *Albizia procera* (63 in Control compared to 140 in 50 g/L concentration). *Syzygium fruticosum* showed significantly greater vigor index in lower *I. cylindrica* extract concentration (184 in 30 g/L concentration or 180 in 10 g/L concentration) compared to higher concentration (107 in 100 g/L concentration). On the other hand, *Azadirachta indica* showed significantly greater vigor index in lower *I. cylindrica* extract concentration (449 in 30 g/L concentration or 245 in 10 g/L concentration) compared to higher concentration (335 in 100 g/L concentration) (Table 2).

Shoot vigor index of receptor tree species

Azadirachta indica demonstrated a significantly higher vigor index under the control treatment (Control: 305) compared to treatment 30 g/L concentration (382), suggesting a potential inhibitory effect at higher extract concentrations. In contrast, *Ficus hispida* exhibited a reduced vigor index under 40 g/L concentration (56) relative to 30 g/L concentration (35), indicating species-specific responses. Although these differences were not statistically significant in all cases, a general trend of increasing vigor index with higher concentrations of *I. cylindrica* leaves extract was observed in the remaining species (Table 3), implying a possible stimulatory effect depending on species and treatment level.

Eussen and Niemann (1981), had proven that leaf extract of *I. cylindrica* has growth-inhibitory effects. *I. cylindrica* leaves and underground parts also demonstrated inhibitory effects on seedling growth in a variety of different plant species, including *Sida spinosa*, *Brachiaria ramosa*, *Echinochloa crus-galli*, *Cynodon dactylon*, and *Lolium multiflorum* (Koger et al. 2004). The allelopathic effects of extracts from *I. cylindrica* are determined by allelochemicals such as fatty acids, terpenoids and phenolic acids, and alkaloids that have potential to retard the growth of various other plants e.g. *Sida spinosa*, *Oryza sativa*, *Pinus roxburghii*, etc. (Kato-Noguchi 2022, Salim 2020, Salim et al. 2020).

Table 2. Vigor index (root) of receptor plants as affected by different concentrations of *Imperata cylindrica* leaves extracts

Treatment (Concentration of <i>Imperata cylindrica</i> leaf extracts.)	<i>Syzygium fruticosum</i>	<i>Albizia procera</i>	<i>Azadirachta indica</i>	<i>Ficus hispida</i>
Distilled water only-control	141.33 ^{ab}	62.67 ^a	369.48 ^{abc}	104 ^d
10 g/L	180.33 ^b	81 ^a	244.77 ^a	83 ^{cd}
20 g/L	138.33 ^{ab}	38.33 ^a	428.79 ^{bc}	60.33 ^b
30 g/L	183.67 ^b	110.67 ^a	448.21 ^c	66 ^{bc}
40 g/L	156 ^{ab}	93 ^a	316.72 ^{ab}	86 ^{cd}
50 g/L	127.33 ^{ab}	139.67 ^a	289.62 ^a	49 ^b
100 g/L	107.33 ^a	55 ^a	334.63 ^{abc}	27.67 ^a
F-value	2.097	1.302	3.728	13.152

[Note: Different letter(s) beside the mean represent significant differences in different treatments according to duncan’s multiple range test (DMRT) at p=0.05.]

Table 3. Vigor index (shoot) of receptor plants as affected by different concentrations of *Imperata cylindrica* leaf extracts

Treatment (Concentration)	<i>Syzygium fruticosum</i>	<i>Albizia procera</i>	<i>Azadirachta indica</i>	<i>Ficus hispida</i>
Distilled water only-control	261 ^a	202 ^a	304.29 ^a	54.67 ^{ab}
10 g/L	334.2 ^a	206 ^a	263.05 ^a	45.33 ^{ab}
20 g/L	262.67 ^a	131 ^a	371.42 ^a	35 ^{ab}
30 g/L	300.33 ^a	267 ^a	381.69 ^a	34.67 ^a
40 g/L	283 ^a	255 ^a	276.25 ^a	56.33 ^b
50 g/L	250 ^a	332.33 ^a	326.08 ^a	41.33 ^{ab}
100 g/L	271.33 ^a	164 ^a	327.22 ^a	41 ^{ab}
F-value	0.906	1.214	0.95	1.877

[Note: Different letter(s) beside the mean represent significant differences in different treatments according to duncan’s multiple range test (DMRT) at p=0.05.]

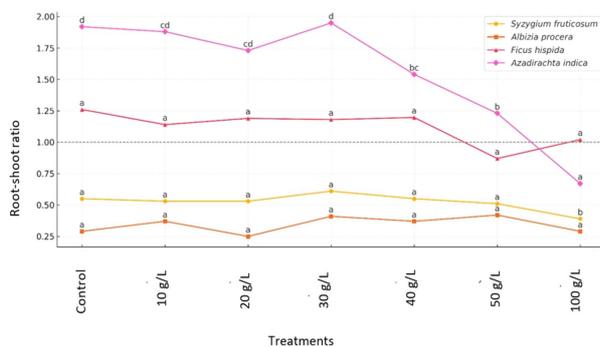


Figure 3. Root-shoot ratio of receptor plants as affected by different concentrations of *Imperata cylindrica* leaf extracts

The root-shoot ratio of receptor tree seedlings

The root-shoot ratios of tree seedlings indicate their survival probability. Seedlings with a ratio less than 1.0 have a lower survival probability. It is evident from the experiment that, *I. cylindrica* extracts did not significantly affect the root-shoot ratios of *Albizia procera* and *Syzygium fruticosum* compared to control treatment, suggesting they did not significantly impact germinated seed growth. *Ficus hispida* and *Azadirachta indica* had a root-shoot ratio of more than one in control and lower in *I. cylindrica* concentration treatments, suggesting they will survive in control conditions or at low concentrations (Figure 3). However, at higher concentrations, they could influence its survival in the future.

Conclusion

The inhibitory impact of *Imperata cylindrica* leaves aqueous extract was higher for *F. hispida* compared to *A. procera* and *A. indica*. Therefore, *A. indica* and *A. procera* may be suggested for planting in the hills infested with *I. cylindrica*. However, green house studies and field studies are needed for drawing definitive conclusions.

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RESEARCH NOTE

Influence of alternative pre- and post-emergent herbicides on weeds and yield of direct-seeded rice

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ABSTRACT

A field experiment was conducted at Research Farm, Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu during *Kharif* 2020 to evaluate the influence of pre- and post-emergence herbicides on weeds and yield of direct-seeded rice. The experiment was laid out in factorial randomized block design with three replications. The treatments evaluated in the study include: pre-emergence application of (PE) pendimethalin 1.0 kg/ha, pyrazosulfuron-ethyl 20 g/ha PE, pretilachlor 600 g/ha PE, pretilachlor + pyrazosulfuron ethyl 615 PE g/ha, post-emergence application (PoE) of bispyribac-sodium 25 g/ha PoE at 25 DAS, penoxsulam + cyhalofop-butyl 135 g/ha PoE at 25 DAS, triafamone + ethoxysulfuron 66.5 g/ha PoE at 25 DAS along with un-weeded control. Major weeds observed were: *Echinochloa* spp., *Dactyloctenium aegyptium*, *Cynodon dactylon*, *Caesulia axillaris*, *Cyperus* spp. and *Phyllanthus niruri*. Pretilachlor + pyrazosulfuron-ethyl 615 g/ha PE recorded significantly lower weed density and dry biomass at harvest with maximum weed control efficiency (87.10 %), higher grain yield, net returns and benefit: cost ratio (1.99). Amongst, post-emergent herbicides, triafamone + ethoxysulfuron 66.5 g/ha PoE at 25 DAS recorded minimum weed density, weed biomass with highest weed control efficiency (82.61%) at harvest, higher rice grain yield, net returns and benefit cost ratio (2.02).

Keywords: Direct-seeded rice, Pretilachlor + pyrazosulfuron-ethyl, Triafamone + ethoxysulfuron, Weed control efficiency, Weed management

Rice is one of the most important staple food crops in the world and more than half of the world's population is dependent on it. It plays a pivotal role in Indian economy. The unavailability of agricultural labourers has become a major problem for transplanting of rice in India (Rao *et al.* 2020). Rice transplantation, which required a large number of labourers, is delayed due to a shortage of labours, and the economics of transplanted rice is under risk (Yadav *et al.* 2011). Concurrently, the high cost of irrigation water and the need of human labour for seedbed preparation, puddling, and transplanting operations reduces the profit margin of transplanted rice production (Rao *et al.* 2017). In addition, the long turn-around time combined with the

unpredictable monsoon results in delayed sowing of succeeding crops (Maity and Mukherjee 2011). Direct-seeding of rice provide opportunity for better mechanization and it mature 7-10 days earlier than transplanted crop. Other benefits of direct-seeded rice include faster and easier planting, improvement of soil health, higher tolerance to water deficit and often higher profit in areas with an assured water supply (Rao *et al.* 2007). Despite its many advantages, direct-seeded rice (DSR) has a number of production challenges, the most serious of which is severe weed infestation (Rao *et al.* 2007, Chauhan 2012). Weeds can reduce rice yield by 40 to 100 per cent in direct-seeded rice (Rao *et al.* 2007). Uncontrolled weeds decrease yield by 61% in wet DSR and 96 per cent in dry DSR. (Rathika *et al.* 2020). Herbicides are considered an alternative/supplement to hand weeding. Use of herbicides has now become an important component of weed management in direct-seeded rice. The use of herbicides gives selective and effective control of weeds and allows the crop to emerge in a relatively weed free environment. However, the use of a single herbicide does not provide effective and season-long weed control and may result in shifts to tolerant weed

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species. Bispyribac-sodium for example, controls *Echinochloa colona*. but does not provide effective control of *Leptochloa chinensis*. and *Dactyloctenium aegyptium* (Chauhan and Abugho 2012). Application of herbicides in sequence (pre-emergence followed by post-emergence) or a mixture of two or more broad-spectrum herbicides along with other cultural practices provides a season-long effective weed control and good yield in DSR (Maity and Mukherjee 2008, Mahajan and Chauhan 2013). Therefore, this study was conducted with an objective to evaluate the efficacy of pre- and post-emergence herbicides in DSR and identify most effective and economical option for successful weed management in DSR.

A field experiment was conducted during *Kharif* season of 2020 at Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu under irrigated conditions. The soil of the experimental field was sandy clay loam in texture with slightly alkaline in reaction (pH 7.75), low in organic carbon (4.68 g/kg) and available nitrogen (247.5 kg/ha) but medium in available phosphorus (14.05 kg/ha) and potassium (128.50 kg/ha). The experiment was laid out in factorial randomized block design with two factor and three replications. The first factor consisted of pre-emergence application (PE) of herbicides, *viz.* pendimethalin 1.0 kg/ha; pyrazosulfuron-ethyl 20 g/ha; pretilachlor 600 g/ha; pretilachlor + pyrazosulfuron-ethyl 615 g/ha and un-weeded control and second factor consist of post-emergence application (PoE) of herbicides *viz.* bispyribac-sodium 25 g/ha at 25 days after sowing (DAS); penoxsulam + cyhalofop-butyl 135 g/ha at 25 DAS, triafamone + ethoxysulfuron 66.5 g/ha at 25 DAS.

Rice crop variety '*Basmati-370*' was sown on 15th June 2020, with a row to row spacing of 20 cm.

The crop was harvested on 3rd November 2020. The recommended dose of NPK (30:20:10 kg/ha) was applied as per package of practices of the university. Irrigation was applied at regular intervals in rice as per need. The pre-emergence application of herbicides was done applied on the next day of sowing and post emergence herbicides were applied at 25 DAS. Observations on weeds were recorded at 30, 60, 90 DAS and at harvest. In each plot, grasses, broad-leaved weeds and sedges were counted from 2 randomly selected places using a 0.5 × 0.5 m quadrat. Weed count was expressed as weed density (no./m²) and subjected to square-root transformation to normalize their distribution. The weeds removed from the selected areas were dried at 65 °C to obtain constant weight and the weight was expressed weed biomass (g/m²). Weed control efficiency (WCE) was calculated by using the formulae suggested by Mishra and Mishra (1997). The crop was harvested from a net plot of from the individual plot, sun dried for 5-6 days and was subsequently threshed and cleaned. The grain thus obtained, were weighed and expressed in tons/hectare. Harvest index was calculated by dividing the economic yield to the biological yield as per the formula given by Nichiporovich (1967). The benefit-cost ratio (B:C) was calculated by dividing the gross income by the cost of cultivation. Data collected during the study were statistically analysed by using the technique of analysis of variance.

The most dominating weed species found throughout the crop growth period in experimental plots were: *Echinochloa* species., *Dactyloctenium aegyptium* and *Cynodon dactylon* amongst grassy weeds; *Caesulia axillaries* amongst broad-leaved weeds, *Cyperus* species, amongst sedges. *Phyllanthus niruri*, was also observed in experimental field during crop season.

Table 1. Effect of pre- and post-emergence herbicides on total weed density (no./m²) in direct-seeded rice

Treatment	30 DAS	60 DAS	90 DAS	At harvest
<i>Factor -A: Pre-emergence herbicides</i>				
Pendimethalin 1.0 kg/ha	5.72 (31.72)	5.05 (24.47)	4.87 (22.75)	4.68 (20.87)
Pyrazosulfuron ethyl 20 g/ha	7.04 (48.51)	6.80 (45.22)	6.76 (44.73)	6.52 (41.46)
Pretilachlor 600 g/ha	6.53 (41.60)	5.86 (33.33)	5.75 (32.06)	5.64 (30.80)
Pretilachlor + pyrazosulfuron ethyl 615 g/ha	5.00 (23.98)	4.03 (15.25)	3.85 (13.86)	3.70 (12.67)
Un-weeded control	7.47 (54.78)	8.60 (72.91)	8.64 (73.72)	8.79 (76.33)
LSD (p=0.05)	0.22	0.33	0.35	0.25
<i>Factor – B: Post-emergence herbicides</i>				
Bispyribac-sodium 25 g/ha 25 DAS	6.32 (38.98)	5.98 (34.72)	5.88 (33.55)	5.93 (34.12)
Penoxsulam + cyhalofop – butyl 135 g/ha 25 DAS	6.36 (39.39)	5.03 (24.30)	4.85 (22.52)	4.69 (20.99)
Triafamone + ethoxysulfuron 66.5 g/ha 25 DAS	6.29 (38.60)	4.42 (18.55)	4.25 (17.04)	4.07 (15.55)
Un-weeded control	6.43 (40.33)	8.83 (77.03)	8.94 (78.94)	8.78 (76.04)
LSD (p=0.05)	NS	0.30	0.31	0.22

Data was subjected to square root transformation ($\sqrt{x+1}$). Original values are in parentheses; DAS: days after seeding

Effect on weeds

All the pre-emergence herbicides treatments showed significant effect weed density and biomass at 30, 60, 90 DAS and at harvest (Table 1 and 2). Among the pre-emergence herbicides pretilachlor + pyrazosulfuron-ethyl 615 g/ha recorded significantly lowest total weed density, biomass and highest weed control efficiency at 30 DAS and 60 DAS than other herbicides treatment and highest weed density and biomass were recorded in un-weeded control. The post-emergence herbicides treatments failed to show any significant impact on density and biomass of total weeds at 30 DAS. Amongst post-emergence herbicides, triafamone + ethoxysulfuron 66.5 g/ha at 25 DAS treatments, recorded significantly lower density of total weed density, biomass and higher weed control efficiency than all other herbicides. Similar trend was recorded at 90 DAS and at harvest. This could be due to the broad-spectrum control of weeds provided by combined application of herbicides with different mode of action. These results are in conformity with Singh *et al.* (2018), who reported that combined application of tank-mix or ready-mix more effective than single herbicides. When these two ready-mix herbicides are applied to the field, the efficacy of these herbicides increases compared to their sole application with a significant inhibitory effect on weed flora in transplanted rice. This study results confirm findings of Raj *et al.* (2013), Deivasigamani (2016), and Menon *et al.* (2017).

Effect on rice yield

All the pre- and post-emergence herbicides caused significant effect on grain yield and straw yield of direct-seeded rice (Table 3). Among pre-

emergence herbicides, pretilachlor + pyrazosulfuron-ethyl 615 g/ha recorded highest yield which was found to be statistically at par with pendimethalin 1.0 kg/ha PE and significantly higher than pyrazosulfuron-ethyl 20 g/ha PE, pretilachlor 600 g/ha PE and un-weeded control. It might be due to lower weed biomass and higher weed control efficiency and better utilization of nutrient and growth factors which ultimately resulted in higher yield of direct-seeded rice confirming the findings of Mishra and Singh (2012). Amongst, post-emergence herbicides, triafamone + ethoxysulfuron 66.5 g/ha at 25 DAS recorded significantly higher yield which was statistically at par with penoxsulam + cyhalofop-butyl 135 g/ha at 25 DAS, whereas, lowest value was recorded with un-weeded control. Increase in yield attributes, *viz.* number of panicles/m², number of grains/panicles, 1000-grain weight resulted higher grain and straw yield which is attributed by reduced competition for moisture, space, light and nutrients between crop and weeds along with effective control of weeds by combination of post-emergence herbicides as reported by Dhanapal *et al.* (2018) and Ramesha *et al.* (2019).

Economics

The economic evaluation (Table 3) revealed that among the pre-emergence herbicides, pretilachlor + pyrazosulfuron ethyl 615 g/ha generated highest net returns (77379 Rs./ha) and B:C ratio (1.99) followed by pendimethalin 1.0 kg/ha PE. Among the post-emergence herbicide treatments, highest net returns of (76860 Rs./ha) and B:C ratio (2.02) was recorded with triafamone + ethoxysulfuron 66.5 g/ha at 25 DAS followed by penoxsulam + cyhalofop-butyl 135 g/ha at 25 and bispyribac-sodium 25 g/ha at 25 DAS.

Table 2. Effect of pre- and post-emergence herbicides on weed biomass (g/m²) and weed control efficiency (WCE) of direct-seeded rice

Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	Weed biomass (g/m ²)	WCE (%)	Weed biomass (g/m ²)	WCE (%)	Weed biomass (g/m ²)	WCE (%)	Weed biomass (g/m ²)	WCE (%)
<i>Factor -A: Pre-emergence herbicides</i>								
Pendimethalin 1.0 kg/ha	2.94(7.6)	72.97	6.14(37)	76.11	7.35(53)	78.26	7.14(50)	78.99
Pyrazosulfuron-ethyl 20 g/ha	3.65(12.3)	56.42	8.22(66)	56.74	10.18(103)	57.89	9.88(97)	59.37
Pretilachlor 600 g/ha	3.35(10.2)	63.85	7.12(50)	67.68	8.65(74)	69.73	8.58(73)	69.46
Pretilachlor + pyrazosulfuron-ethyl 615 g/ha	2.38(4.7)	83.52	4.98(24)	84.50	5.82(33)	86.50	5.63(31)	87.10
Un-weeded control	5.41(28.3)	-	12.44(154)	-	15.65(244)	-	15.46(238)	-
LSD (p=0.05)	0.18	-	0.32	-	0.57	-	0.19	-
<i>Factor - B: Post-emergence herbicides</i>								
Bispyribac-sodium 25 g/ha 25 DAS	3.56(11.7)	5.81	6.83(46)	69.64	8.33(68)	71.38	8.11(65)	72.41
Penoxsulam + cyhalofop-butyl 135 g/ha 25 DAS	3.52(11.4)	8.07	6.39(40)	73.49	7.62(57)	76.11	7.42(54)	76.98
Triafamone + ethoxysulfuron 66.5 g/ha 25 DAS	3.46(11.0)	11.46	5.60(30)	79.80	6.68(44)	81.74	6.47(41)	82.61
Un-weeded control	3.66(12.4)	-	12.30(150)	-	15.49(239)	-	15.36(235)	-
LSD (p=0.05)	NS	-	0.29	-	0.51	-	0.17	-

Data was subjected to square root transformation ($\sqrt{x+1}$). Original values are in parentheses; DAS: days after seeding

Table 3. Effect of pre- and post-emergence herbicides on grain yield, straw yield, harvest index and economics of direct-seeded rice

Treatment	Grain yield (t/ha)	Straw yield (t/ha)	Harvest index (%)	Cost of cultivation (x10 ³ Rs/ha)	Gross returns (x10 ³ Rs/ha)	Net returns (x10 ³ Rs/ha)	B:C Ratio
<i>Factor -A: Pre-emergence herbicides</i>							
Pendimethalin 1.0 kg/ha	2.28	4.09	35.70	37.78	111.21	73.43	1.94
Pyrazosulfuron-ethyl 20 g/ha	2.05	3.69	35.77	37.03	99.99	62.96	1.70
Pretilachlor 600 g/ha	2.17	3.87	35.98	37.08	105.72	68.64	1.85
Pretilachlor + pyrazosulfuron-ethyl 615 g/ha	2.39	4.15	36.38	38.74	116.12	77.38	1.99
Un-weeded control	1.66	3.12	34.97	35.65	81.11	45.46	1.27
LSD (p=0.05)	0.11	0.18	NS	-	-	-	-
<i>Factor -B: Post-emergence herbicides</i>							
Bispyribac-sodium 25 g/ha at 25 DAS	2.20	3.97	35.63	37.29	107.43	70.14	1.88
Penoxsulam + cyhalofop-butyl 135 g/ha 25 DAS	2.30	4.13	35.69	39.14	112.25	73.12	1.86
Triafamone + ethoxysulfuron 66.5 g/ha 25 DAS	2.36	4.16	36.15	37.95	114.81	76.86	2.02
Un-weeded control	1.57	2.87	35.57	34.65	76.83	42.18	1.21
LSD (p=0.05)	0.10	0.16	NS	-	-	-	-

Comparatively higher grain yield attained might be the reason for better net returns and B: C ratio among these treatments as compared to other treatments as observed by Mahajan and Chauhan (2013) and Kashid *et al.* (2016).

Conclusion

It is concluded that among the herbicide treatments evaluated to manage weeds and improve productivity of direct-seeded rice, economically, pretilachlor + pyrazosulfuron-ethyl 615 g/ha PE and triafamone + ethoxysulfuron 66.5 g/ha PoE at 25 DAS were observed to be most promising.

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RESEARCH NOTE

Effect of different weed management methods on weed control and yield of wet-seeded rice seeded by drum seeder

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ABSTRACT

The aim of this study was to evaluate the effectiveness of sequential herbicide applications in combination with mechanical and manual weeding in wet-seeded rice (WSR) seeded by drum seeder during the *Navarai* season (January - April, 2025) at SRM College of Agricultural Sciences, Tamil Nadu, India. A Randomized Block Design replicated three times was used. The sequentially applied pre-emergence application (PE) of bensulfuron-methyl + pretilachlor 660 g/ha followed by (*fb*) post-emergence application (PoE) of floryprauxifen-benzyl + cyhalofop-butyl 150 g/ha recorded the lowest weed density and biomass at all the recorded dates of 20, 40, 60 days after seeding (DAS) with highest weed control efficiency (82.4%), grain yield and straw yield of WSR seeded by drum seeder.

Keywords: Drum seeder, Bensulfuron-methyl + pretilachlor, Trifamone + ethoxysulfuron, Floryprauxifen-benzyl + cyhalofop-butyl, Paddy power weeder, Wet-seeded rice

Rice, the staple food for most of the world's population. Globally, approximately 168.36 million hectares are cultivated with rice, yielding around 799.99 million tons, with an average productivity of 4.7 t/ha (FAOSTAT 2023). In India, rice is highly significant, covering 47.82 million hectares and producing 137.82 million tons, with an average yield of 2.8 t/ha. In Tamil Nadu, rice cultivation spans 21.01 lakh hectares, resulting in a production of 67.99 lakh tons and a productivity rate of 3.2 t/ha (Indiastat 2024). In direct-seeded rice under puddled conditions *i.e.* wet-seeded rice (WSR), most yield reduction is primarily caused by grasses, followed by sedges and broad-leaved weeds (Rathika *et al.* 2020). Weeds are the main barrier to achieving desirable yields in direct-seeded rice (DSR), causing about 50-100% production loss (Rao *et al.* 2007; Verma *et al.* 2023). Consequently, farmers have gradually adopted mechanical and chemical weed management practices, which are cost-effective, require less labor, and are minimally time-consuming (Rao *et al.* 2017). Herbicides are the effective and economic option for weed management in rice (Sekhar *et al.* 2020)

Integrated weed management with herbicides as component in WSR provides a better alternative solution for cost-effective and timely weed control

(Kachroo and Bazaya 2011, Sivasakthi *et al.* 2024). Herbicides with a single mode of action are often ineffective against diverse weed populations. A single herbicide application is frequently insufficient due to the variety of weed species and the risk of herbicide resistance. Therefore, sequential applications of pre- and post-emergence herbicides with different modes of action, combined with manual or mechanical weeding, can effectively manage a wide range of weeds and delay resistance development (Gogoi and Deka 2023). To prevent residue accumulation, shifts in weed flora, and the development of herbicide-resistant weeds, it is recommended to use a variety of herbicides with different compositions that have proven effective in controlling weeds in rice fields (Sekhar *et al.* 2020). The aim of this study was to evaluate the effectiveness of sequential herbicide applications in combination with mechanical and manual weeding in managing weeds and improve productivity of wet-seeded rice (WSR) seeded by drum seeder.

A field experiment was conducted during the *Navarai* season (January - April) of 2025 at the wetland farm of SRM College of Agricultural Sciences, Baburayanpettai, Chengalpattu. Located in Tamil Nadu's Northeastern agro-climatic zone at 12.38° N latitude, 79.73° E longitude, and 50 m above mean sea level. The soil of the experimental field was sandy loam, with low available nitrogen (213.4 kg/ha) and phosphorus (5 kg/ha), medium available

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potassium (140 kg/ha), a pH of 7.5, and an organic carbon content of 0.24%. The short-duration rice variety CO 55 was used as the test variety. The experiment was conducted in a Randomized Block Design (RBD) with three replications. The tested treatment include: pre-emergence application (PE) of bensulfuron-methyl + pretilachlor 660 g/ha on 3 days after seeding (DAS) followed by (*fb*) hand weeding on 40 DAS; bensulfuron-methyl + pretilachlor 660 g/ha PE on 3 DAS *fb* weeding with power weeder on 40 DAS; bensulfuron-methyl + pretilachlor 660 g/ha PE on 3 DAS *fb* post-emergence application (PoE) of florpyrauxifen-benzyl + cyhalofop-butyl 150 g/ha on 25 DAS; early post emergence application (EPoE) of trifamone + ethoxysulfuron 67.5 g/ha on 10 DAS *fb* hand weeding on 40 DAS; trifamone + ethoxysulfuron 67.5 g/ha EPoE on 10 DAS *fb* weeding with power weeder on 40 DAS; trifamone + ethoxysulfuron 67.5 g/ha EPoE on 10 DAS *fb* florpyrauxifen-benzyl + cyhalofop-butyl 150 g/ha on 25 DAS; pretilachlor 500 g/ha PE on 3 DAS *fb* hand weeding on 40 DAS weeding with power weeder 20 DAS and 40 DAS; hand weeding twice 20 DAS and 40 DAS and weedy check control (Unweeded check). All cultural practices, excluding weed management, were followed as per the Crop Production Guide (CPG 2020) recommendations. Data were statistically analyzed as suggested by Gomez and Gomez (1984). Percentage values were

angularly transformed, and weed counts used the ($\sqrt{x+0.5}$) transformation before analysis.

Effect on weeds

The experimental field contained a mixed population of weed species, including grass, sedges and broad-leaved weeds. The dominant grasses were *Echinochloa colona*, *Echinochloa crus-galli* and *Chloris barbata*; sedges included *Cyprus rotundas* and *Cyprus difformis*, while broad-leaved weeds consisted of *Ammania baccifera*, *Eclipta alba*, *Marsilea quadrifolia* and *Phyllanthus niruri*

The lower density, weed intensity and biomass was recorded at 40, 60 DAS with hand weeding twice followed by bensulfuron methyl + pretilachlor 660 g/ha PE *fb* hand weeding on 40 DAS, and bensulfuron methyl + pretilachlor PE *fb* florpyrauxifen-benzyl + cyhalofop-butyl PoE and bensulfuron-methyl + pretilachlor PE *fb* weeding with power weeder on 40 DAS (Table 1). These results are in agreement with Nagarjun *et al.* (2019).

Pretilachlor PE effectively controlled grass weeds broad-leaved weeds and sedges early in crop growth. A reduction in weed density was noted with the use of florpyrauxifen-benzyl + cyhalofop-butyl mixtures rather than a single herbicide. This could be attributed to the efficient management of a diverse range of weed species through two distinct modes of

Table 1. Effect of weed management treatments on total weed density, weed intensity, total weed dry weight, weed control efficiency at 60 DAS in wet-seeded rice

Treatment	Total weed density (no./m ²)			Weed intensity (%)	Total weed biomass (g/m ²)			Weed control efficiency (%)
	Grasses	Sedges	BLW		Grasses	Sedges	BLW	
Bensulfuron methyl + pretilachlor 660 g/ha PE <i>fb</i> hand weeding on 40 DAS	5.07 (20.90)	4.69 (17.74)	5.13 (21.67)	54.67	18.37	11.70	19.14	71.66
Bensulfuron methyl + pretilachlor 660 g/ha PE <i>fb</i> weeding with power weeder on 40 DAS	5.89 (29.28)	5.44 (24.44)	6.15 (31.94)	63.13	29.73	15.82	28.10	59.62
Bensulfuron methyl + pretilachlor 660 g/ha PE <i>fb</i> Florpyrauxifen-benzyl + cyhalofop-butyl 150 g/ha PoE	3.97 (12.00)	3.87 (11.42)	4.27 (14.22)	42.94	11.72	7.80	12.44	82.40
Trifamone + Ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> hand weeding on 40 DAS	5.09 (21.14)	4.85 (18.93)	5.29 (23.05)	55.75	20.27	12.35	20.27	70.12
Trifamone + ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> weeding with power weeder on 40 DAS	6.49 (35.95)	5.49 (25.03)	6.62 (37.54)	66.31	31.73	17.10	29.84	53.51
Trifamone + ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> florpyrauxifen-benzyl + cyhalofop-butyl 150 g/ha PoE	4.70 (17.66)	4.51 (16.51)	4.86 (19.04)	51.34	16.44	9.52	17.10	74.99
Pretilachlor 500 g/ha PE <i>fb</i> hand weeding on 40 DAS	5.45 (24.47)	4.94 (19.79)	5.45 (24.65)	57.82	21.85	13.43	21.75	68.00
Weeding with power weeder 20 DAS and 40 DAS	6.82 (40.03)	6.07 (31.05)	6.65 (37.87)	68.51	38.29	20.80	33.93	48.54
Hand weeding twice 20 DAS and 40 DAS	5.50 (25.03)	5.27 (22.76)	5.82 (28.28)	60.34	23.75	14.30	23.14	64.26
Weedy check control	9.04 (73.47)	8.44 (63.46)	9.38 (78.98)	81.02	74.67	41.99	62.64	0.00
LSD (p=0.05)	0.57	0.56	0.55	6.51	4.57	1.43	4.37	

* Data is subjected to square root transformation. Values in the parenthesis are original; PE – pre-emergence application, PoE – post-emergence application, EPoE - early post-emergence application, *fb* - followed by, BLW = broad-leaved weeds, DAS - days after seeding

action. The weedy check control recorded greater density of grasses, sedges, and broad-leaved weeds due to uncontrolled and enhanced growth of weeds.

At 20 DAS, hand weeding twice recorded the highest weed control efficiency (82.87%), followed by bensulfuron-methyl + pretilachlor (PE) *fb* hand weeding on 40 DAS (77.73%) highlighting their efficacy of early weed suppression. At 40 and 60 DAS, bensulfuron-methyl + pretilachlor 660 g/ha PE *fb* PoE florypyrauxifen-benzyl + cyhalofop-butyl exhibited the highest weed control efficiency (83.04% and 82.40%), indicating persistent weed suppression over time. The triafamone + ethoxysulfuron EPoE *fb* florypyrauxifen-benzyl + cyhalofop-butyl PoE also recorded higher weed control efficiencies of 76.65% and 74.99%, making it the second most effective option.

The application of bensulfuron methyl + pretilachlor PE *fb* florypyrauxifen-benzyl + cyhalofop-butyl PoE effectively managed weeds due to application of herbicides at initial and later stages of crop growth. The pre-emergence application of herbicides effectively managed the early stages of weed growth, while post-emergence application of herbicides controlled them at later stages. Application of florypyrauxifen-benzyl + cyhalofop-butyl resulted in increased weed control efficiency (Perumal *et al.* 2025a). This could be attributed to the effective management of weeds during the crucial period of

their competition. These observations align with the results reported by Munnoli *et al.* (2018) (Table 1)

Effect on rice yield and economics

The highest grain yield of WSR was achieved by applying bensulfuron methyl + pretilachlor PE *fb* florypyrauxifen-benzyl + cyhalofop-butyl PoE (Table 2) due to the broad-spectrum and effective weed control provided by these herbicides as reported by Yogananda *et al.* (2021) and Perumal *et al.* (2025b).

The cost of cultivation, gross return, net return, and benefit-cost (B:C) ratio in WSR with different weed management treatments varied (Table 2). The highest cost was with hand weeding twice due to higher labour requirements, followed by triafamone + ethoxysulfuron 67.5 g/ha EPoE *fb* hand weeding owing to combined use of herbicides and manual weeding.

The highest gross return, net return and B:C ratio in wet-seeded rice were recorded with bensulfuron-methyl + pretilachlor 660 g/ha PE *fb* florypyrauxifen-benzyl + cyhalofop-butyl 150 g/ha PoE and next highest gross return, net return and B:C ratio were recorded was observed with triafamone + ethoxysulfuron 67.5 g/ha EPoE *fb* florypyrauxifen-benzyl + cyhalofop-butyl PoE. The weedy check had the lowest gross income, net income and lowest B:C ratio due to greater weed competition.

Table 2. Effect of different weed management treatments on grain yield, straw yield, harvest index and economics of wet-seeded rice

Treatment	Grain yield	Straw yield	Harvest index	Total cultivation cost (₹/ha)	Net income (₹/ha)	B:C Ratio
Bensulfuron-methyl + pretilachlor 660 g/ha PE <i>fb</i> hand weeding on 40 DAS	4772	6346	0.43	59149	67370	2.13
Bensulfuron methyl + pretilachlor 660 g/ha PE <i>fb</i> weeding with power weeder on 40 DAS	4012	5697	0.41	52299	45500	1.86
Bensulfuron-methyl + pretilachlor 660 g/ha PE <i>fb</i> florypyrauxifen-benzyl + cyhalofop-butyl 150 g/ha PoE	5550	7215	0.44	56449	97053	2.71
Trifamone + ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> hand weeding on 40 DAS	4440	5949	0.43	60274	59662	1.98
Trifamone + ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> weeding with power weeder on 40 DAS	3862	5599	0.41	53424	37774	1.70
Trifamone + ethoxysulfuron 67.5 g/ha EPoE <i>fb</i> florypyrauxifen-benzyl + cyhalofop-butyl 150 g/ha PoE	5128	6720	0.43	57574	82932	2.44
Pretilachlor 500 g/ha PE <i>fb</i> hand weeding on 40 DAS	4262	5711	0.43	57849	54426	1.94
Weeding with power weeder 20 DAS and 40 DAS	3312	4968	0.40	51399	33513	1.65
Hand weeding twice 20 DAS and 40 DAS	4110	5671	0.42	65099	40255	1.61
Weedy check control	1246	2055	0.38	47599	-14517	0.69
LSD (p=0.05)	333	483	NS			

* PE – pre-emergence application, PoE – post-emergence application, EPoE - early post-emergence application, *fb* - followed by, DAS = days after seeding

Based on this study, sequential application of bensulfuron-methyl + pretilachlor PE fb florpiauxifen-benzyl + cyhalofop-butyl PoE proved to be the effective and economic option to manage weeds in wet-seeded rice seeded by drum seeder.

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RESEARCH NOTE

Weed management in summer pearl millet with non-chemical methods and herbicides at middle Gujarat region

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ABSTRACT

A field experiment was carried out to study the effect of pre- and post-emergence herbicides on weeds and pearl millet productivity at the Agronomy Farm, B.A. College of Agriculture, Anand Agricultural University, Anand, Gujarat during the summer season of 2023. The soil of the experimental field was loamy sand in texture. The inter cultivation (IC) followed by (*fb*) hand weeding (HW) at 15 and 30 days after sowing (DAS) caused maximum reduction in the weed density, dry biomass and weed index (WI), higher weed control efficiency (WCE) and pearl millet grain yield. All the tested herbicides significantly reduced the weed growth. The pre-emergence application (PE) of atrazine 750 g/ha and atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE were found effective in managing weeds resulting in higher pearl millet grain yield, net returns and benefit-cost ratio.

Keywords: Atrazine, Non-chemical methods, Pearl millet, Pendimethalin, Weed management, Yield

Pearl millet (*Pennisetum glaucum* L.) is a major coarse grain crop mostly grown in arid and semi-arid climatic conditions. It is one of the most draught-tolerant crops, also known as bulrush millet, bajra, or candle millet and has been grown for food and fodder purposes. It is mostly cultivated in India, Pakistan, Nepal, Nigeria, Niger, Mali etc. In India, pearl millet is cultivated in 7.21-million-hectare area with an average production of 10.83 million tons and productivity of 2.72 t/ha (MoA&FW 2025). India is the largest producer of pearl millet in the world. Grains contain 67 g carbohydrates, 12 g protein, 5 g fat, 242 mg phosphorous, 42 mg calcium, 8 mg iron, and 1 g crude fiber per 100 g (Porwal *et al.* 2023). Pearl millet is sensitive to weeds competition during the initial period of crop weed competition and weeds are the major constraints to attain higher pearl millet productivity as weeds compete for resources (Samota *et al.* 2022). The critical period of competition for pearl millet is up to 35 days (Thanmai *et al.* 2018) and weeds uncontrolled during the critical period cause yield loss of 16 to 94% (Balyan *et al.* 1993, Banga *et al.* 2000; Rao *et al.* 2014). The prevailing methods of weed management are inter-culturing and hand-weeding, which are not economical due to labour scarcity and high labour wages. The chemical weed management practices

proved which appears to be more economical as well as effective for management of weeds (Samota *et al.* 2022; Rao 2022). Pre-emergence application (PE) of herbicides is effective in controlling weeds in pearl millet (Das *et al.* 2013). Atrazine and pendimethalin are broad-spectrum herbicides and are applied as pre-emergence for weed control. Tank mixing of both these herbicides effectively control most of the weeds. In pearl millet, the pre-emergence application of atrazine was reported to effectively control weeds (Kaur and Singh 2006). The post-emergence application (PoE) of tembotrione is recommended for reducing the density and dry biomass of narrow (including sedges) and broad-leaved weeds (Kumar *et al.* 2022). This study was conducted to assess the efficacy of pre- and post-emergence herbicides to manage complex weed flora in summer pearl millet.

A field study was conducted during the summer season of 2023 at the Agronomy Farm, B.A. College of Agriculture, Anand Agricultural University, Anand, Gujarat. The soil of experimental field is loamy sand soil, low in available nitrogen (216 kg/ha), medium in available phosphorous (42.50 kg/ha) and high in available potassium (208.69 kg/ha) with pH of 8.19. The experiment was laid out on randomized completely block design (RCBD) with three replications and ten treatments having gross plot area of 3.60 x 5.00 m (18 m²) and net plot area of 2.70 x 4.00 m (10.8 m²). The tested treatments were: atrazine 50% WP (atrazine) 500 g/ha (PE); atrazine

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750 g/ha PE; pendimethalin 30% EC (pendimethalin) 500 g/ha PE, atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE; early-post emergence application of (EPoE) atrazine 500 g/ha; tembotrione 42% SC (tembotrione) 84 g/ha EPoE, tembotrione 84 g/ha + atrazine 500 g/ha (tank-mix) EPoE, 2-4, D sodium salt 80% WP (2-4, D sodium salt) 400 g/ha PoE, inter-cultivation (IC) followed by (*fb*) hand weeding (HW) at 15 and 30 DAS and weedy check (control). Pearl millet cultivar *GHB 1129* was sown on 24th February 2023 and harvested on 30th May. Sowing was done by drilling method with the seed rate of 3.75 kg/ha at 45 cm spacing between the rows. Application of fertilizers was done at the recommended dose of 140-40-00 NPK kg/ha. Entire dose of phosphorus and half dose of nitrogen were applied as basal dose in furrows just before sowing and the remaining half dose of nitrogen was applied at 30 DAS. Herbicide spraying was done using battery operated knapsack sprayer fitted with a flat fan type of nozzle using 500 liters of water per hectare. The number of monocots, dicots, sedges and total weeds was counted by placing a 1m² quadrat at a random place in the net plot area. Weeds were dried and the dry weight of the weeds was recorded as weed dry biomass (g/m²). Data on weed density (no./m²) and dry biomass (g/m²) were subjected to square root ($\sqrt{x+1}$) transformation. Weed control efficiency and weed index were calculated for each treatment using the formulas given below.

$$WCE = \frac{WDC - WDT}{WDT} \times 100$$

Where, WCE = Weed control efficiency (%)
WDC = Weed dry weight (g) in control plot
WDT = Weed dry weight (g) in treated plot

$$WI = \frac{X - Y}{X} \times 100$$

Where, WI = Weed index (%)
X = Maximum yield from the treatment
Y = Yield of plot from which weed index is to be calculated

Effect on weeds

The dominant weed flora at the experimental site include: among monocots, *Dactyloctenium aegyptium* (18.92%), *Eragrostis major* (13.51%), *Eleusine indica* (12.16%), *Digitaria sanguinalis* (8.11%) and *Setaria viridis* (4.73%); among dicots *Digera arvensis* (12.16%) was dominant followed by *Chenopodium album* (8.11%), *Phyllanthus niruri* (6.76%), *Amaranthus viridis* (4.05%), *Boerhavia erecta* (2.70%) and *Trianthema monogyna* (2.70%) and among sedges *Cyperus rotundus* (2.03%) and *Cyperus iria* (0.68%).

All the tested weed management treatments significantly lowered the density and dry biomass of weeds in comparison to weedy check at 30 DAS, 60 DAS and at harvest (Table 1 and 2). The dicots were effectively controlled by IC *fb* HW at 15 and 30 DAS. Among herbicides tested, atrazine 750 g/ha PE

Table 1. Effect of weed management treatments on weed density (no./m²) at 30 DAS, 60 DAS and at harvest

Treatment	Weed density (no./m ²)											
	30 DAS				60 DAS				Harvest			
	Monocot	Dicot	Sedges	Total	Monocot	Dicot	Sedges	Total	Monocot	Dicot	Sedges	Total
Atrazine 500 g/ha PE	6.02 (36.00)	2.49 (5.33)	2.68 (6.33)	6.94 (47.66)	6.19 (39.00)	2.49 (5.33)	2.15 (3.66)	6.88 (48.00)	4.27 (17.33)	1.96 (3.00)	2.41 (5.00)	5.12 (25.33)
Atrazine 750 g/ha PE	5.22 (26.66)	1.52 (1.33)	2.15 (3.66)	5.68 (31.66)	5.32 (27.66)	1.73 (2.00)	1.82 (2.33)	5.71 (32.00)	3.55 (12.00)	1.41 (1.00)	1.82 (2.33)	4.01 (15.33)
Pendimethalin 500 g/ha PE	1.00 (0.00)	4.60 (20.66)	2.41 (5.00)	5.13 (25.66)	2.22 (4.00)	4.61 (20.66)	2.53 (5.66)	5.58 (30.33)	2.22 (4.00)	2.76 (7.00)	2.69 (6.33)	4.24 (17.33)
Atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE	1.00 (0.00)	2.23 (4.00)	2.94 (7.66)	3.55 (11.66)	1.91 (2.66)	2.15 (3.66)	2.82 (7.00)	3.78 (13.33)	2.13 (3.66)	2.64 (6.00)	2.37 (4.66)	3.91 (14.33)
Atrazine 500 g/ha EPoE	6.97 (48.00)	1.52 (1.33)	3.00 (8.00)	7.61 (57.33)	6.32 (39.66)	1.82 (2.33)	2.93 (7.66)	7.08 (49.66)	4.57 (20.00)	1.90 (2.66)	2.37 (4.66)	5.31 (27.33)
Tembotrione 84 g/ha EPoE	5.32 (28.66)	3.37 (10.66)	2.49 (5.33)	6.65 (44.66)	6.02 (36.00)	2.87 (7.33)	2.30 (4.33)	6.93 (47.66)	4.39 (18.66)	2.49 (5.33)	1.52 (1.33)	5.11 (25.33)
Tembotrione 84 g/ha + atrazine 400 g/ha (tank-mix) EPoE	5.19 (26.66)	1.41 (1.00)	2.15 (3.66)	5.64 (31.33)	5.61 (31.66)	1.98 (3.00)	1.71 (2.00)	6.07 (36.66)	4.26 (17.66)	1.68 (2.00)	2.50 (5.33)	5.08 (25.00)
2,4-D sodium salt 400 g/ha PoE	7.77 (60.00)	4.56 (20.00)	1.00 (0.00)	8.96 (80.00)	6.74 (46.66)	2.29 (4.66)	1.41 (1.00)	7.12 (52.33)	4.91 (23.33)	2.94 (7.66)	1.62 (1.66)	5.78 (32.66)
IC <i>fb</i> HW at 15 and 30 DAS	1.00 (0.00)	1.00 (0.00)	1.62 (1.66)	1.62 (1.66)	1.82 (2.33)	1.79 (2.33)	1.52 (1.33)	2.61 (6.00)	1.98 (3.00)	1.71 (2.00)	2.06 (3.33)	3.05 (8.33)
Weedy check (control)	9.40 (88.00)	7.52 (56.00)	2.23 (4.00)	12.18 (148.00)	7.13 (50.00)	3.53 (11.66)	2.23 (4.00)	8.15 (65.66)	4.81 (23.66)	3.82 (14.00)	2.13 (3.66)	6.47 (41.33)
LSD (p=0.05)	1.45	0.80	0.49	1.43	1.70	0.73	0.42	1.70	1.15	0.76	0.48	0.88

IC = intercultivation; HW = hand weeding; DAS = days after seedin; PE = pre-emergence; EPoE = early post-emergence

Table 2. Effect of weed management treatments on weed dry biomass (g/m²) at 30 DAS, 60 DAS and at harvest

Treatment	Weed dry biomass (g/m ²)											
	30 DAS				60 DAS				Harvest			
	Monocot	Dicot	Sedges	Total	Monocot	Dicot	Sedges	Total	Monocot	Dicot	Sedges	Total
Atrazine 500 g/ha PE	3.89 (14.83)	1.04 (0.09)	1.92 (2.93)	4.29 (17.85)	6.61 (43.41)	3.52 (11.61)	2.14 (3.61)	7.69 (58.64)	7.90 (62.33)	4.40 (18.45)	1.81 (2.28)	9.12 (83.06)
Atrazine 750 g/ha PE	3.27 (9.84)	1.04 (0.08)	1.82 (2.40)	3.62 (12.33)	4.87 (23.08)	1.96 (2.97)	1.99 (3.07)	5.48 (29.13)	6.14 (39.37)	2.94 (7.77)	1.63 (1.67)	6.93 (48.81)
Pendimethalin 500 g/ha PE	1.00 (0.00)	2.70 (6.50)	1.63 (1.74)	3.01 (8.24)	2.36 (4.74)	4.93 (23.51)	2.51 (5.39)	5.87 (33.65)	4.89 (23.28)	5.19 (26.00)	2.31 (4.39)	7.37 (53.67)
Atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE	1.00 (0.00)	1.26 (0.62)	2.18 (3.86)	2.31 (4.48)	2.02 (3.13)	3.12 (8.82)	2.48 (5.17)	4.25 (17.12)	4.38 (18.70)	3.91 (14.70)	2.05 (3.26)	6.08 (36.67)
Atrazine 500 g/ha EPoE	4.85 (22.65)	1.09 (0.19)	2.38 (4.90)	5.36 (27.75)	8.01 (63.83)	2.82 (7.02)	2.54 (5.47)	8.76 (76.33)	9.04 (81.88)	4.30 (17.65)	2.11 (3.49)	10.15 (103.02)
Tembotrione 84 g/ha EPoE	2.43 (4.98)	1.26 (0.60)	1.82 (2.4)	2.99 (8.05)	6.27 (39.11)	5.05 (24.67)	2.00 (3.02)	8.21 (66.81)	8.01 (64.00)	5.39 (28.21)	1.73 (2.02)	9.72 (94.24)
Tembotrione 84 g/ha + atrazine 500 g/ha (tank-mix) EPoE	2.20 (3.84)	1.07 (0.15)	1.42 (1.05)	2.45 (5.05)	6.09 (36.38)	2.74 (6.54)	1.79 (2.27)	6.77 (45.20)	6.79 (45.73)	3.54 (13.11)	1.77 (2.19)	7.81 (61.04)
2,4-D sodium salt 400 g/ha PoE	4.49 (19.70)	1.77 (2.17)	1.00 (0.00)	4.73 (21.87)	6.67 (44.12)	4.05 (15.77)	1.70 (1.91)	7.87 (61.81)	8.26 (67.57)	4.41 (18.87)	1.70 (1.95)	9.45 (88.39)
IC <i>fb</i> HW at 15 and 30 DAS	1.09 (0.22)	1.00 (0.00)	1.13 (0.28)	1.21 (0.50)	1.59 (1.57)	1.61 (1.62)	1.61 (1.62)	2.40 (4.81)	3.80 (13.70)	2.93 (7.87)	1.77 (2.17)	4.93 (23.75)
Weedy check (Control)	6.27 (39.11)	4.03 (15.40)	2.52 (5.41)	7.77 (59.92)	9.15 (84.07)	5.71 (31.91)	2.56 (5.61)	11.04 (121.59)	10.24 (103.98)	7.44 (54.66)	2.36 (4.63)	12.81 (163.29)
LSD (p=0.05)	0.96	0.39	0.63	0.83	1.46	0.77	0.40	1.19	1.85	1.20	0.32	1.77

*The means of original values are indicated by figures in parentheses. Data subjected to transformation ($\sqrt{x+1}$). PE = pre-emergence application, EPoE = early post-emergence application, IC = inter cultivation, HW = hand weeding, DAS = days after sowing, *fb* = followed by

Table 3. Effect of weed management treatments on weed control efficiency, weed index, grain yield and economics

Treatment	WCE (%)			WI (%)	Grain yield (t/ha)	Gross return (₹/ha)	Net return (₹/ha)	B:C
	30 DAS	60 DAS	Harvest					
	Atrazine 500 g/ha PE	70.2	51.8					
Atrazine 750 g/ha PE	79.4	76.0	70.1	12.10	5.24	122536	81255	2.97
Pendimethalin 500 g/ha PE	86.2	72.3	67.1	32.64	4.01	94850	53584	2.30
Atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE	92.5	85.9	77.5	14.69	5.08	118098	76697	2.85
Atrazine 500 g/ha EPoE	53.7	37.2	36.9	19.87	4.77	110806	69780	2.70
Tembotrione 84 g/ha EPoE	86.6	45.1	42.3	20.39	4.74	109568	65574	2.49
Tembotrione 84 g/ha + Atrazine 500 g/ha (tank-mix) EPoE	91.6	62.8	62.6	25.56	4.43	103180	58676	2.32
2,4-D sodium salt 400 g/ha PoE	63.5	49.2	45.9	17.28	4.93	115836	75133	2.85
IC <i>fb</i> HW at 15 and 30 DAS	99.2	96.0	85.5	-	5.96	136978	88848	2.85
Weedy check (Control)	-	-	-	36.01	3.81	90530	50960	2.29
LSD (p=0.05)	-	-	-	-	0.84	-	-	-

*The means of original values are indicated by figures in parentheses. Data subjected to transformation ($\sqrt{x+1}$). IC = intercultivation; HW = hand weeding; DAS = days after seedin; PE = pre-emergence; EPoE = early post-emergence

significantly lowered weed density and dry biomass of dicots at 30 DAS, 60 DAS and at harvest as reported by Samota *et al.* (2022). The density and dry biomass of sedges were significantly decreased with 2,4-D sodium salt 400 g/ha PoE at 30 DAS and harvest. The significant reduction in the sedge’s density was recorded with tembotrione 84 g/ha EPoE. IC *fb* HW at 15 and 30 DAS significantly reduced total weed density and dry biomass at 30 DAS, 60 DAS and at harvest and recorded highest weed control efficiency (Table 3) as reported by Das *et al.* (2013). It was followed by atrazine 500 g/ha + pendimethalin 250 g/ha (tank mix) PE with lower density and dry biomass of monocot weeds and total weeds at 30 DAS, 60 DAS, at harvest and recorded

highest weed control efficiency with lower value of weed index, which could be due to herbicide mixture of two herbicide having different modes of action as observed by Chaudhary *et al.* (2022). Weedy check registered the highest density and dry biomass of total weeds, lower weed control efficiency and higher weed index as no any weed management practice was adopted resulting in maximum growth of weeds during the entire crop growth period (Bhuva and Detroja 2018, Girase *et al.* (2017) and Samota *et al.* 2022).

Effect on pearl millet grain yield and economics

Among all weed control practices, significantly higher pearl millet yield was recorded with IC *fb* HW

at 15 and 30 DAS, atrazine 750 g/ha PE and atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE with an increase in grain yield of 56%, 37% and 33% respectively as compared to weedy check as also observed by Das *et al.* (2013), Chaudhary *et al.* (2022) and Kumar *et al.* (2019). The highest gross return was recorded with IC fb HW at 15 and 30 DAS, followed by atrazine 750 g/ha PE and atrazine 500 g/ha + pendimethalin 250 g/ha (tank mix) PE. While both net return and B:C were higher with IC fb HW at 15 and 30 DAS and atrazine 750 g/ha PE respectively.

It was concluded that in case of scarcity of labour, atrazine 750 g/ha PE or atrazine 500 g/ha + pendimethalin 250 g/ha (tank-mix) PE provided better for efficient weed management, higher grain yield and economic returns in summer pearl millet.

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RESEARCH NOTE

Effect of integrated weed management methods on weeds and productivity of summer baby corn

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ABSTRACT

A field experiment was carried out at Instructional-cum-Research Farm, Assam Agricultural University, Jorhat during summer 2023 to study the effects of weed management treatments on growth, yield and economics of baby corn. Ten weed management treatments were tested in randomized block design with three replications. Different weed management treatments significantly influenced the weed density and biomass, growth, yield attributes and yield of baby corn. Application of paddy straw mulching 4 t/ha at 1 day after seeding (DAS) followed by (*fb*) earthing-up and weeding at 25 DAS recorded the highest baby corn weight without husk (13.74 g) and cob yield without husk (1.91 t/ha) and green fodder yield (29.32 t/ha). Pre-emergence application (PE) of metribuzin 1.0 kg/ha *fb* hand weeding at 25 DAS recorded the next best cob yield without husk (1.86 t/ha) and green fodder yield (28.72 t/ha) with the highest net return of ₹ 1,64,000/ha and B-C ratio of 3.32 due to low cultivation cost compared to the paddy straw mulching 4 t/ha 1 DAS *fb* earthing-up and weeding at 25 DAS.

Keywords: Baby corn, mulching, herbicide, integrated weed management, weed index

Baby corn (*Zea mays* L.) is the young ear of maize harvested before or just after silk emergence, before fertilization. The de-husked ears, valued for their sweet flavour and crispiness, are consumed as a vegetable. Cultivation of baby corn provides tremendous opportunities for crop diversification, crop intensification, value addition and revenue generation. Weeds are perceived by the farming community as being the greatest cause of yield loss in maize. Yield losses in the range of 50-60% occur owing to the absence of appropriateness, untimely and uncontrolled weed growth in maize fields, and therefore, need immediate attention (Ramesh *et al.* 2017). Manual weeding though very effective in controlling weeds, very often is cumbersome, labour-intensive, expensive and time consuming (Warade *et al.* 2006). Baby corn, being an exhaustive feeder, is generally fertilized heavily and spaced widely, both providing an opportunity for weed infestation which results in a drastic reduction in crop yield. Moreover, slow crop growth at early stage along with frequent irrigation causes the season-long weed infestation and yield reduction by 44% in baby corn (Mandal *et al.* 2004). Systematic development of integrated weed-

management strategies is very important to achieve higher crop production (Rao and Nagamani 2010). The use of herbicides like atrazine, metribuzin has resulted encouraging results in maize. Different mulches can be exploited for weed control in this crop and the different resources lying with the farming community can be used depending upon their availability and suitability. The effects of various weed management practices such as herbicides, mulches on weed growth, and growth and yield of baby corn need to be studied for maximization of baby corn yield by minimizing the weed competition for growth resources. Thus, a field experiment was conducted to assess the effects of various integrated weed management treatments on weeds and productivity of baby corn.

The field experiment was conducted at the Instructional-cum-Research (ICR) Farm, Assam Agricultural University, Jorhat. The farm is situated at 26°45' N latitude and 94°12' E longitude with an altitude of 86.56 meters above the mean sea level. The soil texture of the experimental site was sandy loam, low in available N (262.93 kg/ha), medium in available P (27.48 kg/ha) and medium in available K (147.94 kg/ha) and medium in organic carbon content (0.52 %). The total rainfall received during the crop growing period was 263.80 mm. The 'baby corn'

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hybrid G-5414 was sown on 21 February 2023 with the seed rate 22.5 kg/ha and row to row spacing of 45 cm and plant to plant spacing of 20 cm. Recommended dose of fertilizer (N-P-K 120-60-60 kg/ha) was applied and the full doses of P and K and half dose of nitrogenous fertilizers were applied one day before sowing. The rest of the nitrogenous fertilizers were top dressed during knee-high stage (30 DAS). The first picking of baby corn was done on 21 April 2023 (59 DAS) and subsequent picking continued till 7 May 2023. The experiment consisting of ten weed management treatments was laid out in a randomized block design with three replications. The treatment details are given in **Table 1**. The population of weeds (weed density) was counted at 20, 40 and 60 DAS using a 0.5 m x 0.5 m quadrat and the dry matter of weed (weed biomass) was recorded after drying them in hot air oven at 65 °C till constant dry weight was achieved. The weed density and biomass data were subjected to square root transformation before statistical analysis. Weed control efficiency (WCE), weed control index (WCI) and weed index (WI) were calculated as per the formula given by Sharma (2015).

WEC (%) = $\frac{\text{Weed density in control plot} - \text{weed density in treated plot} \times 100}{\text{weed density in control plot}}$

WCI (%) = $\frac{\text{Weed biomass in control plot} - \text{weed biomass in treated plot} \times 100}{\text{weed biomass in control plot}}$

WI (%) = $\frac{\text{Yield from weed free plot} - \text{yield from treated plot} \times 100}{\text{Yield from weed free plot}}$

Effect on weeds

The mixed weed flora, in the experimental field, comprised of a diverse and competitive weed community including grassy, sedge, and broad-leaved weed species. The dominant grassy weeds were: *Cynodon dactylon*, *Digitaria ciliaris*, *Echinochloa colona*, *Eleusine indica*, and *Paspalum conjugatum*. Only sedge was *Cyperus rotundus*. Among the broad-leaved weeds, *Ageratum houstonianum*, *Alternanthera philoxeroides*, *Oxalis martiana*, and *Polygonum plebeium* were common.

All the weed management treatments significantly reduced the weed density at 20 days interval compared to the weedy check (**Table 1**). At 20 DAS, significantly higher reduction in weed density and weed biomass was recorded with metribuzin 2.0 kg/ha which was found at par with application of paddy straw mulching 4t/ha 1 DAS. At 40 DAS, significantly higher reduction (74%) in weed density was recorded with paddy straw mulching 4t/ha at 1DAS *fb* earthing up and weeding at 25 DAS, compared to the weedy check. The weed density recorded with paddy straw mulching 4t/ha at 1DAS *fb* earthing-up and weeding at 25 DAS was found at par with the treatments involving metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS; earthing-up and weeding at 25 DAS; and with metribuzin 1.0 kg/ha PE *fb* tembotrione 120 g/ha PoE 25 DAS. At 60 DAS, metribuzin 1.0 kg/ha PE *fb* hand-weeding at 40 DAS

Table 1. Effect of weed management treatments on weed density and biomass, WCE, WCI and WI in baby corn

Treatment	Weed density (no./m ²)*			Weed biomass (g/m ²)			WCE (%)	WCI (%)	WI (%)
	20 DAS	40 DAS	60 DAS	20 DAS	40 DAS	60 DAS	60 DAS	60 DAS	
Earthing-up and weeding at 25 DAS	11.21 (125.3)	5.75 (32.7)	7.51 (56.0)	4.45 (19.3)	2.21 (4.4)	3.84 (14.3)	89.45	85.59	18.87
Paddy straw mulching 4 t/ha at 1 DAS	6.67 (44.0)	10.79 (116.0)	11.9 (142.7)	2.71 (6.8)	4.17 (16.9)	4.95 (24.1)	73.12	75.70	19.71
Paddy straw mulching 4 t/ha 1 DAS <i>fb</i> earthing-up and weeding at 25 DAS	6.96 (48.0)	5.69 (32.00)	6.41 (40.7)	2.96 (8.4)	2.17 (4.24)	2.73 (6.9)	92.34	92.99	-0.86
Atrazine 1.0 kg /ha PE	7.06 (49.3)	9.44 (88.67)	12.45 (154.6)	3.02 (8.7)	3.77 (13.8)	5.11 (25.6)	70.85	74.13	21.44
Metribuzin 2.0 kg/ha PE	5.69 (32.0)	7.24 (52.00)	11.96 (142.6)	2.17 (4.2)	3.37 (10.9)	4.78 (22.4)	73.12	77.34	24.97
Metribuzin 1.0 kg/ha PE <i>fb</i> hand-weeding at 25 DAS	7.29 (52.7)	5.87 (34.00)	6.72 (44.7)	3.37 (11.0)	2.08 (3.8)	2.93 (8.1)	91.58	91.89	1.81
Metribuzin 1.0 kg/ha PE <i>fb</i> hand-weeding at 40 DAS	7.24 (52.0)	9.26 (85.33)	6.26 (38.7)	3.33 (10.7)	3.96 (15.3)	2.61 (6.3)	92.71	93.62	8.02
Metribuzin 1.0 kg/ha PE <i>fb</i> tembotrione 120 g/ha PoE at 25 DAS	7.34 (53.3)	5.99 (35.33)	6.87 (46.7)	3.40 (11.2)	2.29 (4.7)	2.92 (8.0)	91.21	91.82	2.32
Control - weedy check	11.91 (141.3)	21.91 (480.0)	23.04 (530.6)	4.85 (23.1)	9.05 (81.5)	9.97 (99.1)	-	-	41.32
Weed free	0.71 (0.0)	0.71 (0.0)	0.71 (0.0)	0.71 (0.0)	0.71 (0.0)	0.71 (0.0)	100.00	100.00	0.00
LSD (p=0.05)	1.18	1.33	1.48	0.61	0.90	1.02	-	-	-

*DAS: days after sowing, *fb*: followed by, PE: pre-emergence application; PoE: post-emergence application; WCE: weed control efficiency, WCI: weed control index, WI: weed index; Transformed values are presented, with figures in parentheses indicating the original values

Table 2. Effect of weed management treatments on baby corn growth, yield attributes and yield and economics of baby corn

Treatment	Plant height at harvest (cm)	LAI at 60 DAS	Cob length without husk (cm)	Cob weight without husk (g)	No. of cob/plant	Cob yield with husk (t/ha)	Cob yield without husk (t/ha)	Green forage yield (t/ha)	Net returns (x10 ³ Rs/ha)	B:C Ratio
Earthing-up and weeding at 25 DAS	132.96	4.29	9.84	10.42	2.44	7.67	1.46	23.15	122.57	2.65
Paddy straw mulching 4 t/ha at 1 DAS	131.21	4.27	9.42	10.85	2.56	7.54	1.43	22.38	103.66	1.69
Paddy straw mulching 4 t/ha 1 DAS <i>fb</i> earthing-up and weeding at 25 DAS	146.50	5.64	11.24	13.74	2.78	9.53	1.91	29.32	156.40	2.45
Atrazine 1.0 kg/ha PE	123.73	4.45	9.45	10.27	2.18	7.38	1.31	21.89	107.37	2.34
Metribuzin 2.0 kg/ha PE	117.40	4.04	9.09	9.67	2.16	7.03	1.28	21.60	96.89	1.83
Metribuzin 1.0 kg/ha PE <i>fb</i> hand-weeding at 25 DAS	138.98	5.49	10.92	12.53	2.78	9.28	1.86	28.72	164.81	3.32
Metribuzin 1.0 kg/ha PE <i>fb</i> tembotrione 120 g/ha PoE at 25 DAS	132.93	4.90	10.58	11.57	2.42	8.67	1.64	26.04	150.48	3.02
Metribuzin 1.0 kg/ha PE <i>fb</i> tembotrione 120 g/ha PoE at 25 DAS	137.58	5.13	10.85	12.13	2.67	9.23	1.80	28.53	158.08	3.11
Control - weedy check	115.55	3.42	8.43	8.65	2.04	5.45	0.96	20.26	72.02	1.62
Weed free	140.54	5.53	11.06	13.20	2.78	9.45	1.87	28.90	158.70	2.77
LSD (p=0.05)	13.39	1.03	1.16	1.76	0.56	1.73	0.26	3.27	-	-

*DAS: days after sowing, *fb*: followed by, PE: pre-emergence application; PoE: post-emergence application

recorded significantly lower weed density, which was found at par with paddy straw mulching 4t/ha at 1DAS. Next effective treatments were paddy straw mulching 4t/ha at 1DAS *fb* earthing-up and weeding at 25 DAS; metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS and metribuzin 1.0 kg/ha PE *fb* tembotrione 120 g/ha PoE at 25 DAS. The lowest weed biomass and weed control efficiency at 40 DAS and 60 DAS was recorded with metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS which was found at par with paddy straw mulching 4t/ha at 1DAS *fb* earthing-up and weeding at 25 DAS; metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS; metribuzin 1.0 kg/ha PE *fb* tembotrione 120 g/ha PoE at 25DAS; and earthing-up and weeding at 25 DAS. The herbicides efficiently managed weeds in the initial stages and the second flush were managed by herbicide or non-chemical method and hence resulted in lesser weed density and biomass in the treatments with the them as components. The initial mulching with paddy straw 4 t/ha at 1DAS *fb* earthing-up and weeding at 25 DAS had a smothering effect on weeds and thereby exhibited lower emergence of weeds at early stages while hand weeding and earthing-up at 25 DAS managed the second flush of weeds which resulted in lower weed density and biomass at 40 and 60 DAS. The reduction in weed density and biomass at critical crop weed competition stage created congenial environment for vigorous baby corn growth and later the crop itself had a smothering effect on weeds grown in the vicinity. The results were in agreement with Mahadevaiah *et al.* (2010), Abdullahi *et al.* (2016), Mishra *et al.* (2016) and Prithwiraj *et al.* (2018). The sole application of atrazine 1.0 kg/ha PE and metribuzin 2.0 kg/ha PE were less effective in

managing weeds as the weeds emerged at later stage of baby corn growth and were remained uncontrolled with these treatments. The results are in the lines of Kandasamy (2017). At 20 DAS, the highest WCI was recorded with metribuzin 2.0 kg/ha PE which was found at par with paddy straw mulching 4 t/ha at 1 DAS. At 40 DAS and 60 DAS, the highest WCI was recorded with 1.0 kg/ha PE *fb* hand-weeding at 25 DAS.

Effect on baby corn

The different weed management treatments significantly enhanced growth parameters as compared to the weedy check (**Table 2**). The tallest plants with highest LAI were recorded with paddy straw mulching at 1 DAS (4t/ha) *fb* earthing-up and weeding at 25 DAS which was found at par with the weed free; metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS and metribuzin 1.0 kg/ha PE *fb* tembotrione 120 g/ha PoE at 25DAS. This might be attributed to lower weed density and biomass under these treatments that created less crop weed competition for growth factors. Similarly, all the weed management treatments improved the yield attributes of baby corn as compared to the weedy check. The treatment with paddy straw mulching 4t/ha at 1 DAS *fb* earthing-up and weeding at 25 DAS recorded the highest yield attributes of baby corn, *viz.* cob length and cob weight, the highest cob yield without husk which was 98.96 % higher over the weedy check and 2.14% higher over the weed free cob yield. The results are in conformity of the findings of Mandal *et al.* (2004). The best treatment was found at par with metribuzin 1.0 kg/ha PE *fb* hand-weeding at 25 DAS and metribuzin 1.0 kg/ha PE *fb* tembotrione 120 g/ha

PoE at 25DAS. The results corroborate with the findings of Abdullahi *et al.* (2016), Dutta *et al.* (2016) and Mandal *et al.* (2004).

It was concluded that paddy straw mulching 4t/ha at 1DAS *fb* earthing-up and weeding at 25 DAS resulted in effective management of weeds as well as the highest cob yield without husk and green fodder yield of baby corn. Metribuzin 1.0 kg/ha PE *fb* hand weeding at 25 DAS recorded the next best cob yield without husk and green fodder yield with the highest net return of ₹ 1,64, 000/ha and B-C ratio of 3.32 due to lower cost of cultivation with this treatment compared to the other high yielding treatments.

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RESEARCH NOTE

Efficacy of herbicides and their combinations in managing mixed weed flora effectively and economically in *Rabi* greengram

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ABSTRACT

A field experiment was conducted at Regional Agricultural Research Station, Lam, Acharya N.G. Ranga Agricultural University, Guntur Andhra Pradesh India during *Rabi* 2023-24, to evaluate the efficacy of herbicides and their combinations and identify the suitable effective and economical pre-and post-emergence herbicides options in *Rabi* greengram, to manage mixed weed flora including certain weeds such as *Chrozophora rotleri*, *Cardiospermum helicacabum* and *Phyllanthus maderaspatensis*. which are not controlled by recommended herbicides. Significantly lower weed density and biomass with higher weed control efficiency (WCE), greengram yield components, seed yield and benefit-cost ratio were obtained with post-emergence (PoE) application of fomesafen + fluazifop-p-butyl 222 g/ha and sodium-acifluorfen + clodinafop-propargyl 185 g/ha PoE. These treatments were effective in controlling mixed weed flora including broad-leaved weeds that were not controlled by imazethapyr.

Keywords: Diclosulam, Greengram, Fomesafen + fluazifop-p-butyl, Herbicide mixtures, Sodium-acifluorfen + clodinafop-propargyl, Weed management

Greengram (*Vigna radiate* L.) plays an important role not only in human diet, but also in improving the soil fertility through biological nitrogen fixation with *Rhizobium* (Das *et al.* 2024). The lowest productivity of greengram is mainly due to non-adoption of good crop husbandry practices by the farming community.

The *Rabi* greengram is subjected to heavy infestation of weeds and their competition due to its short duration and relatively slow initial growth. Weed infestation is the one of major constraints in greengram cultivation and the extent of yield loss due to heavy weed infestation in *rabi* greengram is about 10 to 45% (Rao and Chauhan 2015).

Initial weed free situation is essential for greengram as the critical period of crop-weed competition is up to 20-30 DAS (Singh and Singh 2020). Due to shortage of human labour and high wages, manual weeding is not a feasible and economical practice. In spite of the pre-and-post emergence herbicides are available for control of weeds in greengram (Maji *et al.* 2025), there is large variation in weed flora associated in *Kharif* and *Rabi* greengram due to rainfall pattern or irrigation

schedule adopted. The pre-emergence application (PE) of pendimethalin and imazethapyr at recommended doses and pendimethalin + imazethapyr 1.0 kg/ha (Kumar *et al.* 2019) failed to control certain broad-leaved weed species like *Phyllanthus maderaspatensis*, *Cardiospermum helicacabum* and *Chrozophora rotleri*, which are dominant in *Rabi* greengram on vertisols. This might be due to change in cropping rotations like dry direct-seeded rice preceding to greengram and adoption of zero till pulse cultivation in black soils of Coastal Andhra Pradesh.

In the recent years, new generation low dose and high efficiency pre-emergence herbicides like pyroxasulfone and diclosulam or ready-mix herbicides are available to control the weeds in greengram with better selectivity and broad-spectrum weed control as well as low mammalian toxicity. However, their performance varied due to type of soil and weed flora associated with greengram. Hence, there is a need to evaluate new generation pre-emergence and post-emergence herbicide mixtures, alternative to pendimethalin and imazethapyr for broad-spectrum weed control in greengram on vertisols of Krishna Zone of Andhra Pradesh. Thus, a study was conducted to evaluate the efficacy of pre-and post-emergence herbicides and their combinations to identify the suitable effective and economical option to manage weeds in *Rabi* greengram.

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The field experiment was conducted at Regional Agricultural Research Station, Lam campus of Acharya N.G. Ranga Agricultural University, Lam, Guntur, Andhra Pradesh, India during *Rabi*, 2023-24. The experimental site is situated at 16.36° N latitude and 80.43° E longitude at an altitude of 33 m above the mean sea level in the Krishna Zone of Andhra Pradesh. A total of 187.2 mm of rainfall was received during crop growth period in two rainy days. The soil was black clay loam in texture, neutral in reaction, low in organic carbon and available nitrogen, medium in available phosphorous and available potassium. The experiment was laid out in a randomized block design with twelve treatments, replicated thrice. The tested treatments include: pre-emergence application (PE) of pyroxasulfone 125 g/ha; diclosulam 20 g/ha PE; metolachlor 1200 g/ha PE; pendimethalin 1000 g/ha PE; post-emergence application (PoE) of imazethapyr 50 g/ha + clethodim 125 g/ha (TM); imazethapyr 50 g/ha + haloxyfop-r-butyl 125 g/ha (RM) PoE; fomesafen + fluazifop-p-butyl (RM) 222 g/ha PoE; imazethapyr + imazamox (RM) 75 g/ha PoE; sodium-acifluorfen + clodinafop-propargyl (RM) 185 g/ha PoE applied at 20 DAS; pendimethalin 1000 g/ha PE followed by (*fb*) imazethapyr 50 g/ha PoE at 20 DAS, hand weeding twice at 20 and 40 days after seeding (DAS) and unweeded check. The gross plots size was 4.8 m × 4.0 m and the crop was sown at spacing of 30 cm × 10 cm. The greengram variety 'LGG-607' was used. The required quantities of pre-and post-emergence herbicides were applied at one and 20 DAS, respectively using spray fluid 500 l/ha with the help of knapsack sprayer fitted with flat fan nozzle. The data on weed density, weed biomass, greengram yield components and seed yield were recorded as per the standard methods. The greengram phytotoxicity was assessed using a scale of 1 to 10 where 0 indicates no crop injury and 10 indicate complete crop destruction.

The diversified weed flora associated with *Rabi* greengram in clay soils were *Echinochloa colona*, *Leptochloa chinensis* and *Dinebra retroflexa* among the grasses, *Chrozophora rotleri*, *Phyllanthus maderaspatensis*, *Cardiospermum helicacabum*, *Trianthema portulacastrum*, *Euphorbia geniculata*, *Commelina benghalensis*, *Digera arvensis*, *Cleome viscosa*, *Amaranthus viridis*, *Portulaca oleracea* and *Phyllanthus niruri* among the broad-leaved weeds; and *Cyperus rotundus* and *Cyperus iria* among the sedges. All the weed management treatments significantly influenced weed density and weed biomass. Among the weed management treatments tested, significantly lower density and biomass of grasses, sedges, broad-leaved weeds and total weeds as well as higher weed control efficiency were obtained with hand weeding twice at 20 and 40 DAS,

which were at par with fomesafen + fluazifop-p-butyl 222 g/ha PoE and sodium-acifluorfen + clodinafop-propargyl 185 g/ha PoE applied at 20 DAS (**Table 1**). This might be due to better control of all categories of weeds including *Chrozophora rotleri*, *Phyllanthus maderaspatensis* and *Cardiospermum helicacabum* because of dual mode of action of herbicide mixtures (Tej Pratap *et al.* 2024). Imazethapyr 50 g/ha + clethodim 125 g/ha PoE was the next best treatment which was at par with imazethapyr 50 g/ha + haloxyfop-R-butyl 125 g/ha PoE. The tested herbicide mixtures registered significantly lesser weed density and biomass than pre-emergence herbicides.

The higher weed control efficiency (WCE) was observed with fomesafen + fluazifop-p-butyl 222 g/ha PoE followed by sodium-acifluorfen + clodinafop-propargyl 185 g/ha PoE and pendimethalin 1000 g/ha PE *fb* imazethapyr 1000+50 g/ha PoE. The weed control efficiency with hand weeding twice was lower than above herbicide treatments. Pre-emergence herbicides registered lower weed control efficiency than all PoE herbicides.

Different pre-and post-emergence herbicides significantly influenced the greengram yield components and seed yield (**Table 2**). The highest values of greengram yield components, seed yield, haulm yield and harvest index were recorded with hand weeding twice at 20 and 40 DAS which was comparable with fomesafen + fluazifop-p-butyl 222 g/ha PoE and sodium-acifluorfen + clodinafop-propargyl 185 g/ha PoE. This might be due to broad-spectrum of weed control during critical period of crop growth which enhanced the better translocation of photosynthates from source to pods and then to seeds. The seed yield of greengram was increased by 63.08, 60.35, 58.72% with hand weeding twice at 20 and 40 DAS, fomesafen + fluazifop-p-butyl 222 g/ha PoE and sodium-acifluorfen + clodinafop-propargyl 185g/ha PoE, respectively compared to unweeded check. These results are in agreement with results of Maji *et al.* (2025). All the PoE herbicides out yielded higher yield components and yield compared to PE herbicides applied in greengram. The lowest values of yield components and seed yield of greengram were obtained with unweeded check, which was significantly lesser than rest of the weed management practices. All the post-emergence herbicides did not show any phytotoxicity on greengram. Among all the PE herbicides, diclosulam 20 g/ha and pyroxasulfone 125 g/ha usage resulted in phytotoxicity rating of '2' (discoloration and stunting) '1' (slight injury) in 0-10 scale in greengram. However, greengram crop plants were recovered from phytotoxicity within 15 days after their application.

Table 1. Weed density, weed biomass and weed control efficiency (WCE) as influenced by pre-and post-emergence herbicides in *Rabi* greengram

Treatment	Weed density (no./m ²) at harvest				Weed biomass (g/m ²) at harvest				WCE (%)
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	
Pyroxasulfone 125 g/ha PE	6.0(35.3)	3.4(11.0)	5.6(30.7)	8.8(77.0)	3.7(13.1)	2.9(8.0)	4.9(24.0)	6.7(45.1)	45.20
Diclosulam 20 g/ha PE	6.6(43.0)	1.0(0.7)	5.8(33.3)	10.0(104.3)	4.0(15.9)	1.0(0.4)	5.2(26.3)	6.6(42.7)	48.18
Metolachlor 1200 g/ha PE	7.3(55.7)	4.1(16.3)	7.5(55.5)	11.2(127.7)	4.6(20.6)	3.5(11.9)	6.3(38.7)	8.5(71.2)	13.57
Pendimethalin 1000 g/ha PE	6.7(45.3)	3.6(12.7)	6.8(46.0)	10.2(104.0)	3.7(13.4)	3.1(9.2)	6.1(36.3)	7.7(59.0)	28.40
Imazethapyr 50 g/ha + clethodim 125 g/ha (TM) PoE	4.1(16.3)	2.7(6.7)	4.1(16.0)	6.3(39.0)	2.5(6.0)	2.3(4.8)	3.6(12.4)	4.9(23.2)	71.81
Imazethapyr 50 g/ha + haloxyfop-R-methyl 105 g/ha (TM) PoE	4.7(21.7)	2.8(7.7)	4.3(18.0)	6.9(47.0)	2.9(8.0)	2.4(5.4)	3.8(14.2)	5.3(27.7)	66.40
Fomesafen + fluazifop-p-butyl 222 g/ha (RM) PoE	3.3(10.3)	2.1(4.0)	3.4(11.0)	5.1(26.0)	2.1(3.8)	1.8(2.9)	3.0(8.7)	4.0(15.4)	81.30
Imazethapyr + imazamox 75 g/ha (RM) PoE	5.5(30.3)	3.1(9.0)	4.8(22.7)	7.9(61.7)	3.4(11.0)	2.6(6.6)	4.3(17.8)	6.0(35.5)	56.86
Sodium-acifluorfen + clodinafop-propargyl 185 g/ha (RM) PoE	3.5(12.0)	1.9(3.0)	3.5(11.7)	5.2(26.7)	2.2(4.4)	1.6(2.2)	3.1(9.2)	4.0(15.5)	80.82
Pendimethalin 1000 g/ha PE <i>fb</i> imazethapyr 50 g/ha PoE	3.9(15.0)	2.2(4.3)	3.7(13.0)	5.7(32.3)	2.4(5.5)	1.2(0.9)	3.3(10.3)	4.1(16.8)	79.65
Hand weeding twice at 20 and 40 DAS	3.2(10.0)	1.2(1.0)	2.9(8.0)	4.4(19.0)	2.0(3.7)	1.1(0.7)	4.5(20.3)	5.0(24.7)	70.00
Unweeded check	8.4(69.7)	4.0(15.3)	7.1(50.7)	11.6(134.0)	5.1(25.7)	3.6(12.6)	6.7(43.9)	9.1(82.3)	-
LSD (p=0.05)	1.21	0.45	0.59	1.63	0.56	0.38	0.39	0.50	

Data given in parenthesis are original values and subjected to square root transformation. WCE: weed control efficiency; TM: tank-mix; RM: ready-mix; BLWs=Broad-leaved weeds; PE=pre-emergence application; PoE=post-emergence application *fb*=followed by; DAS=days after sowing

Table 2. Greengram yield components and yield as influenced by pre-and post-emergence herbicides

Treatment	No of pods/plant	No of seeds/plant	Pod length (cm)	No of seeds/plant	100 seed weight (g)	Seed yield (kg/ha)	Haulm yield (kg/ha)	Harvest index (%)	Weed index (%)	Benefit-cost ratio
Pyroxasulfone 125 g/ha PE	7.76	9.01	7.01	69.91	3.83	764	1222	38.47	33.80	1.95
Diclosulam 20 g/ha PE	8.11	9.12	7.14	73.80	3.98	785	1256	38.46	31.98	2.15
Metolachlor 1200 g/ha PE	7.62	8.64	6.62	65.83	3.61	712	995	38.47	38.30	1.67
Pendimethalin 1000 g/ha PE	7.67	8.87	6.85	67.85	3.74	710	1136	38.46	38.47	1.95
Imazethapyr 50 g/ha + clethodim 125 g/ha (TM) PoE	9.44	9.33	7.86	88.07	4.18	885	1368	39.28	23.31	2.26
Imazethapyr 50 g/ha + haloxyfop-R-methyl 105 g/ha (TM) PoE	8.77	9.28	7.54	81.38	4.1	810	1296	38.46	29.81	2.07
Fomesafen + fluazifop-p-butyl 222 g/ha (RM) PoE	11.10	9.86	8.23	109.4	4.84	1074	1675	39.07	6.93	2.90
Imazethapyr + imazamox 75 g/ha (RM) PoE	8.40	9.14	7.25	81.06	4.01	801	1282	38.45	30.59	2.12
Sodium-acifluorfen + clodinafop-propargyl 185 g/ha (RM) PoE	10.14	9.65	8.14	97.85	4.46	1032	1651	38.46	10.57	2.81
Pendimethalin 1000 g/ha PE <i>fb</i> imazethapyr 50 g/ha PoE	9.63	9.4	8.05	90.52	4.22	954	1526	38.47	17.33	2.51
Hand weeding twice at 20 and 40 DAS	11.93	10.46	8.54	124.7	4.92	1154	1710	40.29	-	2.29
Unweeded check	5.15	7.14	5.02	36.77	3.17	426	805	34.64	63.08	1.25
LSD (p=0.05)	1.72	1.61	0.98	11.23	0.98	143	284	0.46	-	0.53

TM: tank-mix RM; ready-mix; PE = pre-emergence application; PoE = post-emergence application *fb* = followed by; DAS= days after sowing

The percent reduction in seed yield due to weed infestation was higher with unweeded check. Among the weed management treatments tested, the highest benefit-cost ratio was observed with fomesafen + fluazifop-p-butyl 222 g/ha PoE which was statistically at par with sodium-acifluorfen + clodinafop-propargyl 185 g/ha PoE due to increased economic yield and low cost associated with these treatments. Benefit-cost ratio obtained with hand weeding twice at 20 and 40 DAS was lesser than above two best weed management practices due to increased cost of weeding.

It was concluded that in *Rabi* greengram on clay soils, fomesafen + fluazifop-p-butyl 222 g/ha PoE and sodium-acifluorfen + clodinafop-propargyl 118 g/ha PoE applied at 20 DAS effectively and economically managed broad-spectrum of weeds and recorded higher greengram seed yield and benefit-cost ratio.

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RESEARCH NOTE

Weeds, castor yield attributes and yield as influenced by weed management

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ABSTRACT

A field experiment was conducted at Agricultural College Farm, Bapatla, Andhra Pradesh during *Kharif* 2020 to assess the effect of weed management treatments on weeds, yield attributes and yield of castor. The hand weeding twice at 20 and 40 days after seeding (DAS) recorded the lowest density and biomass of all the categories of weeds as well as the highest weed control efficiency, yield attributes and yield of castor. Next best treatments were pre-emergence application (PE) of alachlor 1.5 kg/ha followed by (*fb*) post-emergence application (PoE) chlorimuron-ethyl 10 g + propaquizafop 63 g/ha at 30 DAS or alachlor 1.5 kg/ha PE *fb* application of halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS. The benefit cost ratio was highest with alachlor 1.5 kg/ha PE *fb* halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS.

Keywords: Alachlor, castor, chlorimuron-ethyl + propaquizafop, halosulfuron-methyl + propaquizafop, Weed control efficiency

Castor (*Ricinus communis* L.), is a member of the Euphorbiaceae family and the most archaic non-edible oilseed crop. Castor oil has been used almost entirely for pharmaceutical and industrial applications. Castor is grown in tropical, subtropical and temperate areas. India is the world's leading producer, accounting for 68% and 85% of global acreage and production, respectively, ahead of China and Brazil. India produced 19,79,718 tons of castor seed from 10,19,279 hectares with a productivity of 1.94 t/ha during 2023-24 (FAOSTAT 2025). The major castor producing states of India are Gujarat, Rajasthan, Andhra Pradesh and Telangana.

Castor productivity is influenced by a variety of agronomic factors. Weed management is the major limiting factor for achieving optimal castor productivity and production. Castor plants are particularly sensitive to weed competition because to their slow initial development as weeds compete available nutrients and other resources during the early growth phases, causing considerable yield losses up to 30-60 % (Mishra *et al.* 2016, Kalaichelvi and Senthil Kumar 2016, Naik *et al.* 2016). Considering the castor crop should be kept weed free up to initial 90 days after sowing, which is more crucial for crop-weed competition (Patel *et al.* 2014). Thus, weed control during the critical period of crop growth is a vital for successful castor production

(Mishra *et al.* 2016). Herbicides were proved to be a viable option and play a critical role in weed management in castor as herbicides are effective, selective, cost effective and efficient in controlling weeds when used alone or in combination with other weed control methods (Kalaichelvi and Senthil Kumar 2016). The use of herbicides as pre-emergence treatments, either alone or in combination followed by one or more post-emergence treatments, can be an effective method for weed control (Naik *et al.* 2016). This study was conducted with an objective to identify suitable herbicides either alone or as sequential application for managing weeds and improve the productivity of castor.

This study was conducted during the *Kharif*, 2020 at the Agricultural College Farm in Bapatla, Andhra Pradesh. The soil had a clay texture, a neutral reaction, medium organic carbon, low available nitrogen, medium available phosphorus and potassium. The experiment was set up in a Randomized Block Design, with ten treatments, *viz.* weedy check, hand weeding twice at 20 and 40 days after seeding (DAS), pre-emergence application (PE) of alachlor 1.5 kg/ha; post-emergence application (PoE) of chlorimuron-ethyl 10 g/ha at 20 DAS, halosulfuron-methyl 67.5 g/ha PoE at 20 DAS; propaquizafop 63 g/ha PoE at 30 DAS; alachlor 1.5 kg/ha PE followed by (*fb*) chlorimuron-ethyl 10 g/ha PoE at 30 DAS; alachlor 1.5 kg/ha PE *fb* halosulfuron-methyl 67.5 g/ha PoE at 30 DAS; alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS; alachlor 1.5

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kg/ha PE *fb* halosulfuron- methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS. The castor hybrid (PCH-111) was sown at 90 x 60 cm spacing by hand dibbling method. Gap filling and thinning were completed at 10 DAS. A 60-40-30 kg N-P₂O₅-K₂O/ha fertilizer dose was applied in the form of urea, single superphosphate and muriate of potash, respectively. Using the pocketing approach, nitrogen was supplied in three equal split (30, 60 and 90 DAS), and potassium and phosphorus were applied basally at the time of planting. One day after seeding, pre-emergence herbicide (alachlor) was sprayed. The post-emergence herbicides (chlorimuron-ethyl, halosulfuron-methyl and propaquizafop) were sprayed at 20 and 30 DAS as per the treatments, using a backpack sprayer equipped with a flood jet nozzle. Category wise weed density and biomass were recorded using quadrat of 1x1 m² at 45 DAS and at harvest. Statistical significance was tested by F value at 5 per cent level of probability and the critical difference was worked out wherever the effects were significant. In view of the larger variation in the recorded values of weed density and biomass, the corresponding data were subjected to square root transformation ($\sqrt{x+0.5}$), weed control efficiency and weed index were subjected to angular transformation before subjecting to statistical analysis, as suggested by Gomez and Gomez (1984).

The predominant weed species observed in the experimental field of castor were *Celosia argentea*, *Phyllanthus niruri*, *Euphorbia hirta*, *Trianthema*

portulacastrum, *Tridax procumbens*, *Alternanthera philoxeroides* and *Cardiospermum helicacabum*, among broad- leaved weeds; *Cynodon dactylon*, among grasses and *Cyperus rotundus* among sedges.

Effect on weeds

The minimum density and biomass of grasses, sedges and broad-leaved weeds and higher weed control efficiency were recorded with hand weeding twice at 20 and 40 DAS, which was on a par with alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS, alachlor 1.5 kg/ha PE *fb* halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS and propaquizafop 63 g/ha PoE at 30 DAS (Table 1). At 45 DAS and at harvest a similar trend of treatments effect was observed in density and biomass of grasses, sedges, broad-leaved weeds and total weeds. Halosulfuron-methyl effectively controlled the sedges and turf weeds, while propaquizafop was found to control the annual and perennial grasses. The sequential application of pre-emergence application followed by tank-mix of two herbicides as post-emergence application was found to be effective in controlling broad spectrum of weeds, compared to sole application of an herbicide either as pre- or post-emergence as observed in the present study. The highest density and biomass of total weeds was recorded in weedy check which can be attributed to the absence of control measures and optimal conditions for weed growth and reproduction.

Table 1. Density and biomass of weeds and weed control efficiency at 45 DAS as influenced by different weed management treatments

Treatment	Weed density (no./m ²)				Weed dry matter (kg/ha)				Weed control efficiency (%)
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	
Weedy check	9.7 (94.7)	7.5 (55.3)	8.0 (64.0)	14.6 (214.0)	11.4 (130.4)	8.3 (67.9)	6.6 (42.8)	15.5 (241.1)	-
Hand weeding twice at 20 and 40 DAS	2.6 (6.4)	2.7 (6.7)	2.7 (6.7)	4.5 (19.7)	1.5 (1.8)	1.5 (1.7)	1.6 (2.1)	2.5 (5.6)	97.7
Alachlor 1.5 kg/ha PE	6.7 (44.0)	7.2 (52.0)	7.0 (49.3)	12.1 (145.3)	8.3 (69.2)	7.3 (53.3)	5.6 (31.1)	12.4 (153.6)	36.3
Chlorimuron-ethyl 10 g/ha PoE at 20 DAS	7.9 (61.9)	5.8 (33.7)	4.1 (16.3)	10.6 (111.9)	9.0 (80.3)	6.0 (35.2)	2.6 (6.5)	11.1 (122.0)	49.4
Halosulfuron-methyl 67.5 g/ha PoE at 20 DAS	7.6 (58.3)	3.8 (14.3)	5.8 (32.7)	10.3 (105.3)	8.5 (72.3)	2.4 (5.3)	4.7 (21.5)	10.0 (99.2)	58.9
Propaquizafop 63 g/ha PoE at 30 DAS	3.2 (9.9)	7.2 (51.7)	7.9 (62.3)	11.1 (123.9)	1.7 (2.6)	7.4 (54.5)	6.4 (40.8)	9.9 (98.0)	59.4
Alachlor 1.5 kg/ha PE <i>fb</i> chlorimuron-ethyl 10 g/ha PoE at 30 DAS	6.3 (39.1)	5.1 (25.3)	3.1 (9.0)	8.6 (73.4)	7.7 (58.6)	5.7 (32.5)	2.3 (4.6)	9.8 (95.8)	60.3
Alachlor 1.5 kg/ha PE <i>fb</i> halosulfuron-methyl 67.5 g/ha PoE at 30 DAS	6.1 (37.0)	3.3 (10.7)	4.6 (21.0)	8.3 (68.7)	7.5 (56.5)	1.7 (2.7)	4.2 (17.3)	8.8 (76.6)	68.2
Alachlor 1.5 kg/ha PE <i>fb</i> chlorimuron-ethyl 10 g + Propaquizafop 63 g/ha PoE at 30 DAS	2.8 (7.3)	4.8 (22.3)	3.0 (8.3)	6.2 (38.0)	1.5 (2.0)	3.9 (15.4)	1.6 (2.2)	4.5 (19.6)	91.9
Alachlor 1.5 kg/ha PE <i>fb</i> halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS.	2.8 (7.6)	3.2 (10.0)	4.8 (22.3)	6.4 (39.9)	1.7 (2.4)	1.6 (2.3)	4.3 (18.2)	4.8 (22.9)	90.5
LSD (p=0.05)	0.9	0.8	0.9	0.9	1.0	0.8	0.9	1.1	5.1

Data in parentheses are original values, which are transformed to ($\sqrt{x+0.5}$) and analysed statistically, *fb*=followed by; DAS = days after seeding; PE = pre-emergence application; PoE= post-emergence application

Table 2. Castor yield attributes, yield and economics as influenced by different weed management treatments in castor

Treatment	No. of spikes/plant	No. of capsules/spike	Spike length (cm)	Test weight (g)	Seed yield (t/ha)	Weed index (%)	Net returns (Rs/ha)	B:C ratio
Weedy check	4.7	61.6	32.9	25.9	1.35	45.5	26942	1.14
Hand weeding twice at 20 and 40 DAS	7.7	93.3	47.4	30.5	2.48	-	60895	1.90
Alachlor 1.5 kg/ha PE	5.2	64.7	34.8	26.6	1.62	34.6	35287	1.38
Chlorimuron-ethyl 10 g/ha PoE at 20 DAS	5.2	77.6	35.2	25.5	1.88	24.1	46509	1.93
Halosulfuron-methyl 67.5 g/ha PoE at 20 DAS	5.3	75.6	34.7	26.4	1.83	26.3	41047	1.49
Propaquizafop 63 g/ha PoE at 30 DAS	5.3	78.0	35.8	27.0	1.94	21.8	47658	1.90
Alachlor 1.5 kg/ha PE <i>fb</i> chlorimuron-ethyl 10 g/ha PoE at 30 DAS	5.7	81.0	39.4	28.4	2.12	14.7	53429	2.06
Alachlor 1.5 kg/ha PE <i>fb</i> halosulfuron-methyl 67.5 g/ha PoE at 30 DAS	5.6	79.5	38.8	28.7	2.06	16.8	48130	1.64
Alachlor 1.5 kg/ha PE <i>fb</i> chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS	7.0	85.6	43.0	29.5	2.39	3.8	62276	2.29
Alachlor 1.5 kg/ha PE <i>fb</i> halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS.	6.6	83.9	41.7	28.9	2.33	6.3	56589	1.85
LSD (p=0.05)	1.3	11.6	6.7	NS	0.25	10.5	9466	0.33

NS=Not Significant.; *fb*=followed by; DAS = days after seeding; PE = pre-emergence application; PoE= post-emergence application

Effect on crop

The castor yield attributes, viz. number of spikes/plant, number of capsules/spike, spike length (cm), seed yield and economics were significantly influenced by different weed management practices (Table 2). The test weight of castor was not significantly influenced by different weed management treatments. Among the tested weed management treatments, significantly the higher values of yield attributes and yield of castor were recorded with hand weeding at 20 and 40 DAS followed by alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS and alachlor 1.5 kg/ha PE *fb* halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha as PoE 30 DAS. The timely management of weeds by these treatments resulted in reduction in weed impact especially during the critical period of crop weed competition resulting in better foliage development, which finally reflected in the highest values of yield and yield attributes. Significantly the lowest values of yield attributes were observed under weedy check. The lowest weed index observed in hand weeding at 20 and 40 DAS is due to complete removal of weeds at critical period of crop weed competition. Among the herbicide treatments, the lowest weed index was noticed with alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS confirming the findings of Patel *et al.* (2014). The highest benefit cost ratio was observed with alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS (Table 2).

It was concluded that alachlor 1.5 kg/ha PE *fb* chlorimuron-ethyl 10 g + propaquizafop 63 g/ha PoE at 30 DAS or alachlor 1.5 kg/ha PE *fb* halosulfuron-methyl 67.5 g + propaquizafop 63 g/ha PoE at 30 DAS or hand weeding twice at 20 and 40 DAS recorded effective weed control with higher castor yield attributes and seed yield.

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