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RESEARCH ARTICLE

Integrated weed management enhanced the aerobic rice performance by suppressing weeds at critical competition period with low residue herbicides

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Abstract

Aerobic rice is a newly evolved agro technique for enhanced yield and water productivity which is threatened by higher weed infestation affecting the crop yield and quality. Sole herbicide usage for weed management leads to higher chemical load on the ecosystem distressing the soil ecology. To address this issue, the present study on integrated weed management (IWM) practices in aerobic rice was conducted at Tamil Nadu Agricultural University (TNAU), Coimbatore during *Kharif* 2022. Preliminary study indicated that 30 g/ha of pyrazosulfuron-ethyl and 40 g/ha of bispyribac-sodium were found optimum for weed management. Subsequently, main field experiment was taken up in a randomized block design (RBD) with three replications. Six IWM practices were tested against conventional weed management practices. The results of the study revealed that the pre-emergent application of pyrazosulfuron ethyl *fb* early-post emergent bispyribac sodium *fb* one mechanical weeding upregulated the aerobic rice yields by 2.36 times and net returns to ₹29244/ ha. The enhancement in aerobic rice performance was clearly attributable to reduced weed menace during the critical period of crop weed competition. The same treatment controlled the weeds from sowing till harvest with weed control efficiency and index of 91.19 % and 89.01 % respectively, that improved the rice above and below-ground parameters. The integration of pre- and early post-emergent herbicide along with physical weed removal methods was found to be effective in curbing weed growth, enhancing crop performance and maximizing the net returns with low residue herbicides for subsequent crop under aerobic rice.

Keywords: aerobic rice; critical weed competition period; herbicide residue; IWM; phytotoxicity; yield

Introduction

Water is an integral part of the rice lifecycle that requires around 150 to 200 cm of water per crop season depending upon the soil, climatic factors, varietal characteristics and management practices. Of the world's total irrigated water, 34 - 43 % is diverted towards irrigated lowland rice, which covers 24 - 30% of the world's freshwater (1). With an increasing scarcity of water and decreasing per capita availability of water, there is a critical need for sustainable crop production strategies that enhance resource use efficiency and increase yield. Aerobic rice production is a newly evolved concept to achieve higher yield with less water. It is the cultivation of rice in well-drained fields, by direct dry sowing of paddy seeds alike the rest of upland crops and maintaining the soils in aerated condition (non-flooded) with supplemental irrigation under deficit rainfall, along with well-supplied inputs. Simply, the rice grown in aerobic soil conditions is called aerobic rice (2). The cut in water usage in aerobic rice production ranges from 37 to 50.8 %, in contrast to the puddled transplanted method (3). The additional advantages of aerobic rice are that plants develop extensive and deeper root systems, alongside comparatively enhanced water utilization efficiency, thus witnessing an improved biomass that facilitates higher productivity in water-scarce conditions (4). The lack of standing water helps to reduce the emission of greenhouse gases, thereby decreasing the contribution of rice production towards global warming (5).

The aerobic rice in the absence of standing water allows a higher density of weeds compared to the conventional method. In transplanted rice, the initial flush of weeds is controlled by puddling followed by stagnating water and the crop gets a benefit with improved stand/establishment. The seedlings of rice have a size differential with weeds that emerge sooner or later the transplantation, which reduces weed interference with the crop (6). But in aerobic soils, the crop and weeds emerge simultaneously and thus, weeds have a comparative advantage. They vie for all the essential growth factors like light, space, nutrients and water. The supply of inputs is based on what crop alone will take (crop requirement), which will be adequate for crops when they grow in a competition-free environment. But in the actual field conditions, numerous weeds germinating simultaneously with the crop will invariably exhaust the inputs that are meant for the crop alone. Thus, the scarcity of input / resources arises under field conditions. The competition is felt only when the resources are constrained and one among the competing individuals is stronger in scavenging the scarce resource. The yield of aerobic rice will reduce to a greater extent if left un-weeded. The extent of loss in yield due to improper weed management ranges between 62.2 to 91.7 % (7). The dry matter of weeds exceeding 400 g/m^2 has a drastic effect on rice crop, that it cannot produce any significant yield at all (8). This loss in yield can be overcome by efficient and IWM practices. There are different methods of weed management; of which some are proven effective, some are economical and some others are timesaving.

An IWM strategy combines various practices to achieve effective weed suppression at critical crop-weed competition period while ensuring environmental safety and farmer-friendliness (9). Relying on a single weed control method often proves insufficient for comprehensive weed management; thus, integrating multiple strategies in a coordinated manner is the need of the hour. The practices should be integrated such that, there will be improved efficacy of weed control over the single practice, reduced effects on the natural flora and fauna, cost-effective and should witness a productive increase in crop growth in terms of yield. Recently, the usage of herbicides has increased and they have been famed for polluting the environment and causing a drastic effect on natural ecosystems. Several studies have shown very little quantity (about <1 %) of herbicides is enough to suppress weed growth once they have reached the specific target site (10). Now, the question arises, where does the remaining amount of herbicide reside? This necessitates the in-detail study of the entire life cycle of that chemical from being sprayed to its complete elimination (degradation) from the environment. Every herbicide has its own time of persistence in the soil before it has degraded below detectable levels. The health of various living beings including humans can be affected adversely by the accumulation of these herbicide residues in crop produce (11). The herbicides even contaminate groundwater by leaching below the sub-surfaces and reach water bodies through runoff, where they affect aquatic life too.

In aerobic rice cultivation, weeds emerge throughout the crop's growth period, creating ongoing competition. While several studies investigated various weed managing practices for aerobic rice, there lies a significant need to explore the effectiveness of integrating different herbicides through sequential applications combined with hand weeding (HW) or mechanical weeding (MW) methods. This approach is crucial for managing weed competition especially during the early and critical stages of crop development, wherein the presence of weeds can severely impact yields. Furthermore, research on herbicide residues in aerobic rice systems is currently limited. Considering the importance of both effective weed management and the implications of herbicide residues, this study aimed to evaluate various IWM practices for their impact on aerobic rice performance and the residual levels of herbicides in the soil.

Material and Methods

The preliminary study was conducted during January-February 2022 in Field F6 at the Wetland Farm, Department of Agronomy, TNAU, Coimbatore, for assessing the phytotoxicity of herbicides on rice seedlings. The aim was to evaluate the impact of different doses of herbicides, specifically pyrazosulfuron ethyl and bispyribac sodium on direct-seeded aerobic rice variety CO (R) 53, which is suitable for drought conditions. The study involved nine treatments, with four different doses - 10, 20, 30 and 40 g/ha of pyrazosulfuron ethyl (PyrazE.) and three doses of bispyribac sodium (Bispyr.) - 30, 40 and 50 g/ha tested against recommended dose of pendimethalin (Pendi.) and weedy check treatments. PyrazE. was applied as pre-emergent application (PE) on 3rd Days After Sowing (DAS) and Bispyr. was applied as early post-emergence (EPoE) herbicide on 12th DAS. The study was carried out for up to 30 days in Randomized Complete Block Design (RCBD) with three replications, to select optimum dose for main field experiment.

The main field experiment was subsequently carried out during the summer season (March to July) of 2022 in Field F1 at the Wetland Farm, Department of Agronomy, TNAU, Tamil Nadu. This field is situated at a latitude of 11˚1'6" N, a longitude of 76˚58'21" E and an altitude of 426.7 m above mean sea level. The mean annual rainfall recorded at experimental farm was 674.2 mm, distributed over 47 rainy days. During the field experiment, daily mean temperature ranged from a maximum of 33.5 °C to a minimum of 23.6 °C. Mean relative humidity varied between 82.1 % at 07:22 hours and 49.7% at 14:22 hr. The crop period received a total of 102.4 mm of rainfall. The composite soil sample (0 - 15 cm depth) from the experiment field was subjected to various physical and chemical analysis. The results revealed that, the soil texture was clay loam, characterized by low available nitrogen (N), medium available phosphorus (P) and high available potassium (K) (238.3, 12.1 and 408.1 kg/ha respectively) levels. The soil had a pH of 7.74, an electrical conductivity (EC) of 0.38 dS/m and an organic carbon content of 0.67 g/kg.

The main field experiment included six IWM practices and three comparative checks *viz.,* two hand weeding (two HW), two mechanical weeding (two MW) and weedy check (control), constituting a total of nine treatments with three replicates, assessed under RCBD. The PyrazE. and Pendi. were applied as PE spray (3 DAS) and Bispyr. as EPoE spray (12 DAS). All the herbicide treatments were followed by either HW or MW. The details of the treatments imposed along with time schedule is given in Table 1 and the crop husbandary details are presented in Table 2.

Table 1. Treatments under the main experiment

	Treatments	Dose	Time of herbicide application (DAS)
T_1	PE Pendi 30 EC *fb* two HW	1.0 kg/ha	3
T_2	PE PyrazE. 10 WP *fb* two HW	30 g/ha	3
T_3	PE PyrazE. 10 WP *fb* two MW	30 g/ha	3
T_4	EPoE Bispyribac sodium 10 SC *fb* one HW	40 g/ha	12
T_5	EPoE Bispyribac sodium 10 SC *fb* one MW	40 g/ha	12
T_6	PE PyrazE. 10 WP *fb* EPoE Bispyribac sodium 10 SC *fb* one MW	30 g/ha *fb* 40 g/ha	3 and 12
T_7	Two HW	-	-
T_8	Two MW	-	-
T_9	Control (Weedy check)	-	-

*note: one HW or MW was taken up at 45 DAS, while two HW or MW was taken up at 25 and 45 DAS.

Table 2. Crop husbandry details

Particulars	Preliminary study	Main field experiment
Location of the field	F 6	F 1
Spacing	20 cm x 10 cm	
Season	January-February, 2022	March-July, 2022
Gross plot size	1 m x 1 m = 1 m^2	5 m x 3 m = 15 m^2
Net plot size	-	4.2 m x 2.6 m = 10.92 m^2

Observations recorded

Preliminary study

The herbicidal phytotoxicity effects were studied by visual observation of the crop at 7 days after herbicide spray. The ratings were given on a scale of 0 to 10 for different herbicide doses (12). Rice seedling height (cm), dry biomass (g/m^2), weed density (per m^2) and dry biomass (g/m^2) were recorded at 30 DAS.

Main field experiment

Weed species of experimental plot were recorded from control plot (unweeded/weedy check); segregated into grasses and broad-leaved weeds (BLW). Weed density in each plot was recorded by placing a quadrat (0.25 m^2) from four places randomly and expressed as no./m^2. Weeds found within the four quadrats in each plot were pulled out, sun-dried and oven-dried at 65 ± 5 °C for 72 hr or till a constant weight was reached. Then, weighed and the values were expressed in g/m^2. From these group-wise densities and dry biomass, total weed densities and biomass were recorded at 30, 60 and 90 DAS. Weed control efficiency, weed control index and weed index were calculated (13-15). The treatment T6, PE PyrazE. *fb* EPoE Bispyribac sodium *fb* one MW with minimum weeds is taken as reference (treatment recording minimum weeds) for calculating weed index.

$$\text{Weed control efficiency} = \frac{(\text{Weed density in control} - \text{Weed density in treated plot}) \times 100}{\text{Weed density in control}}$$

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

$$\text{Weed index} = \frac{(\text{Yield with minimum weeds} - \text{Yield in the treatment plot}) \times 100}{\text{Yield with minimum weeds}}$$

Crop biometric observations like plant height (cm), plant dry biomass (kg/ha), number of tillers (no./m^2), leaf area index and nutrient uptake (kg/ha) were recorded at 30, 60 and 90 DAS. Root parameters like root length (cm), root dry biomass (g/plant) and root volume (cubic centimetre, by volume displacement method) were assessed at 20, 30 and 40 DAS. Yield parameters like productive tillers (no./m^2), panicle length (cm), panicle weight (g/panicle), number of grains (no./panicle), number of filled grains per panicle (no./panicle), test weight (g/1000 seeds), grain and straw yield (kg/ha) and harvest index were assessed at harvest stage of the crop.

For analysing the herbicide residues, the soil samples were collected from main field treatment plots at an interval of 0 (2 hr after application), 1, 7, 15, 30, 45, 60, 75 and 90 days after herbicide spray. The soil samples were collected from five randomly selected places in the net plot area and were stored in a deep freezer (-20 °C). Later, the herbicides were extracted and analysed using HPLC.

The economics pertaining to the cost of cultivation, gross and net returns as well as B-C ratio were calculated treatment-wise. The prevailing prices during the utilization of all inputs were considered for calculating the cost of cultivation and the minimum support price announced during the experimentation year was regarded for assessing the returns from agricultural products. The following formulas were used to determine the different economic parameters;

(i) Gross return (₹ /ha) =

Economic yield (kg/ha) x Market value of the produce (₹ /kg)

(ii) Net return (₹ /ha) =

Gross return (₹ /ha) - Cost of cultivation (₹ /ha)

(iii) Benefit-cost ratio = Gross returns/ Cost of cultivation

Statistical analysis

The data on weed parameters and crop characteristics recorded under all the treatments were statistically analysed (16). Due to higher variations in the data of weed density and weed dry biomass, they were subjected to square root transformation $(\sqrt{X+0.5})$ and later subjected for statistical analysis. The 5 % probability level was used to calculate the critical difference for statistically different treatments. The non-significant comparison was denoted as 'NS'. The box plots were illustrated as derived from OPSTAT software and the correlation analysis was conducted using R software (Version 4.4.1).

Results

Preliminary study

Phytotoxicity effect of herbicides on rice seedlings

The PE application of four different doses of PyrazE. showed no signs of phytotoxicity on rice seedlings. However, the EPoE application of Bispyr. at 50 g/ha resulted in slight discoloration and stunting symptoms, with a visual phytotoxicity rating of 1. However, 30 g/ha and 40 g/ha of Bispyr. showed no phytotoxicity symptoms (Table 3).

Growth of rice seedlings

At 30 DAS, PE PyrazE. at 40 g/ha resulted in significantly higher seedling height and dry biomass (34.5 cm and 871.5 kg/ha respectively), comparable to 30 g/ha (34.2 cm and 865.2 kg/ha respectively). Among the doses of Bispyr., 40 g/ha achieved a seedling height of 34.5 cm, which was significantly higher and equivalent to 50 g/ha (34.4 cm) (Fig. 1).

Weed menace

In general, dose of herbicide application and weed density were negatively correlated. Weed density and dry biomass decreased with increasing doses of herbicides. The application of PE PyrazE. at 40 g/ha recorded significantly lower weed density and weed dry biomass (16 no./m^2 and 2.38 g/m^2 respectively), which was on par with 30 g/ha (Fig. 2). Among the varied doses of EPoE Bispyr, 50 g/ha reduced the weed density to 22.67 no./m^2 and weed dry biomass to 3.74 g/m^2, that was significantly lower and on par with 40 g/ha (24.00 no./m^2 and 3.91 g/m^2 respectively). The highest weed population and dry biomass were noted in the weedy check (232.00 no./m^2 and 47.36 g/m^2 respectively).

The preliminary study revealed that, PE PyrazE. at 30 g/ha had comparable efficacy with 40 g/ha in seedling growth and weed control, while incurring lower costs per hectare. Similarly, EPoE Bispyr. at 40 g/ha exhibited comparable results with 50 g/ha in seedling growth and weed control, without any phytotoxicity symptoms. Based on these findings, PE PyrazE. at 30 g/ha and EPoE Bispyr. at 40 g/ha were considered ideal for weed management in aerobic rice and were chosen to form IWM practices for main experiment.

Main Field Experiment

Weed flora in aerobic rice field

The weed flora in the experiment field consisted of grasses and BLW, without any notice of sedges (Table 4). Among the grasses, *Echinochloa colona* and *Echinochloa crus-galli* were the dominant species, while *Portulaca oleracea* and *Corchorus olitorius* were predominant among the BLW. Grass were the major constituting weeds among the total weed density (73.8 %) and contributed higher dry biomass than BLW.

Table 3. Effect of different doses of herbicides application on phytotoxicity of rice seedlings at 7 days after herbicide spray

	Treatments	Phytotoxicity ratings
T_1	PE Pendimethalin 30 EC	0
T_2	PE PyrazE. 10 WP	0
T_3	PE PyrazE. 10 WP	0
T_4	PE PyrazE. 10 WP	0
T_5	PE PyrazE.10 WP	0
T_6	EPoE Bispyr. 10 SC	0
T_7	EPoE Bispyr.10 SC	0
T_8	EPoE Bispyr.10 SC	1
T_9	Control (Weedy check)	-

Temporal variations in weed parameters as influenced by different IWM practices

The different IWM practices had significant effects on weed infestation, with their impact varying across different periods of treatment application. The practices involving PE herbicide application at 3 DAS followed by either HW or MW at 25 DAS resulted in lower weed infestation at 30 DAS (Fig. 3). Between the two PE herbicides applied before HW, Pendi. provided better early weed control, reducing weed density and dry biomass by 95.99 % and 95.86 % respectively, compared to the weedy check. The effectiveness of PE PyrazE. varied depending on whether it was followed by HW, MW or an EPoE herbicide application at 12 DAS. HW after PE PyrazE. offered higher weed control efficiency (95.61 %) and weed control index (95.59 %) than MW. However, the combination of PE and EPoE herbicides significantly reduced weed dry biomass by 95.76 % (WCI) at 30 DAS, even without any physical weed removal. The sole application of EPoE Bispyr. had less control over weeds at 30 DAS with least weed control efficiency (~ 90 %) and weed control index (~89 %) among the chemical weeding practices. However, when supplemented with one HW at 45th DAS, the WCE and WCI of EPoE spray increased at 60 DAS, while all other IWM practices showed a diminishing trend. Thus, enhanced the control over weeds mainly during the critical period of crop-weed competition for aerobic rice i.e., between 15 to 45 DAS. Notably, the IWM practices involving either PE or EPoE, followed by HW or sequential herbicide application *fb* MW at 45 DAS recorded more than 90 % of WCE and WCI at 60 DAS. The effect of different IWM practices on weed control diminished gradually over time. Finally at 90 DAS, the IWM practices of either PE Pendi. *fb* two HW or EPoE Bispyr. *fb* one HW or sequential herbicide application with one MW was found to control weeds for the entire crop cycle, with weed control efficiencies above 90 % and weed control index above 85 %.

Temporal variation in crop performance as influenced by different IWM practices

Plant height

The IWM practices had significant variations in plant height that can be mainly attributed to efficient weed control under different practices. The practices involving PE herbicides recorded significantly higher plant height at 30 DAS, which was clearly due to a reduction in weed menace during the initial crop establishment stage.

Among them, PE PyrazE. *fb* EPoE Bispyr. *fb* one MW resulted in 29.7, 35.4 and 52.04 % higher plant height at 30, 60 and 90 DAS respectively over weedy check (Fig. 4). By 60 DAS, EPoE Bispyr. *fb* one HW and PE Pendi. *fb* two HW recorded

Table 4. Composition of weed flora in aerobic rice

S. No.	Botanical name	Common name	Family
	I. Grassy weeds		
1.	*E. colona*	Jungle grass	Poaceae
2.	*E. crus-galli*	Barnyard grass	
3.	*Dinebra retroflexa*	Viper grass	
4.	*Chloris barbata*	Purple top Chloris	
	II. Broad-leaved weeds		
1.	*P. oleracea*	Common purslane	Portulacaceae
2.	*C. olitorius*	Nalta jute	Malvaceae
3.	*Hibiscus vitifolius*	Grape-leaved mallow	
4.	*Amaranthus viridis*	Slender amaranth, pigweed	Amaranthaceae

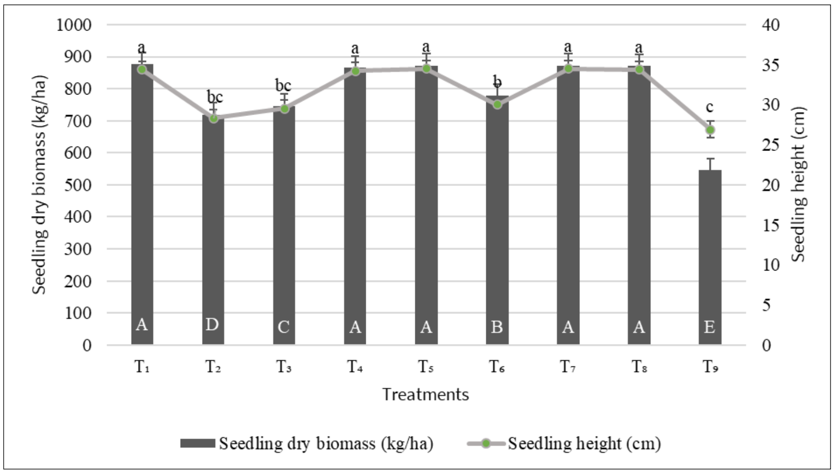


Fig. 1. Variation in rice seedling growth attributes under the influence of different herbicides and their varied doses.

T1 PE Pendimethalin 1.0 kg/ha; T2 PE Pyrazosulfuron ethyl 10 g/ha; T3 PE Pyrazosulfuron ethyl 20 g/ha; T4 PE Pyrazosulfuron ethyl 30 g/ha; T5 PE Pyrazosulfuron ethyl 40 g/ha; T6 EPoE Bispyribac sodium 30 g/ha; T7 EPoE Bispyribac sodium 40 g/ha; T8 EPoE Bispyribac sodium 50 g/ha and T9 Control (weedy check); Different alphabetical letters indicate significant differences; lower case alphabetical letters represent seedling height; upper case alphabetical letters represent seedling dry biomass.

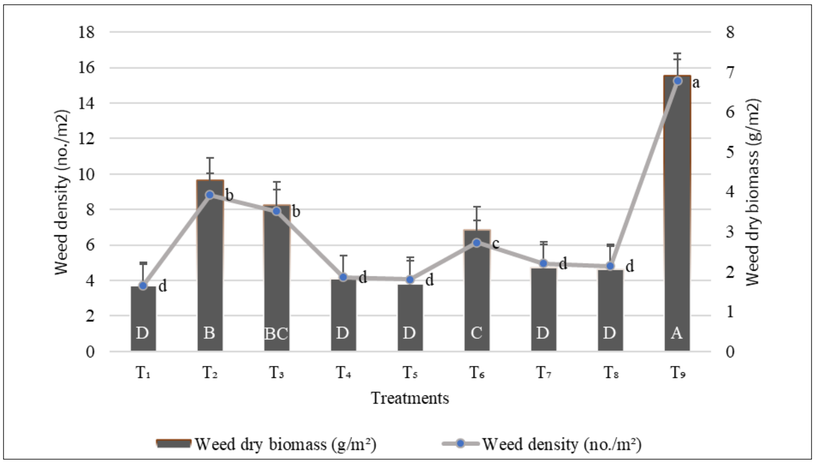


Fig. 2. Variation in weed parameters as influenced by different herbicides and their varied doses.

T1 PE Pendimethalin 1.0 kg/ha; T2 PE Pyrazosulfuron ethyl 10 g/ha; T3 PE Pyrazosulfuron ethyl 20 g/ha; T4 PE Pyrazosulfuron ethyl 30 g/ha; T5 PE Pyrazosulfuron ethyl 40 g/ha; T6 EPoE Bispyribac sodium 30 g/ha; T7 EPoE Bispyribac sodium 40 g/ha; T8 EPoE Bispyribac sodium 50 g/ha and T9 Control (weedy check); Different alphabetical letters indicate significant differences; lower case alphabetical letters represent seedling height; upper case alphabetical letters represent seedling dry biomass.

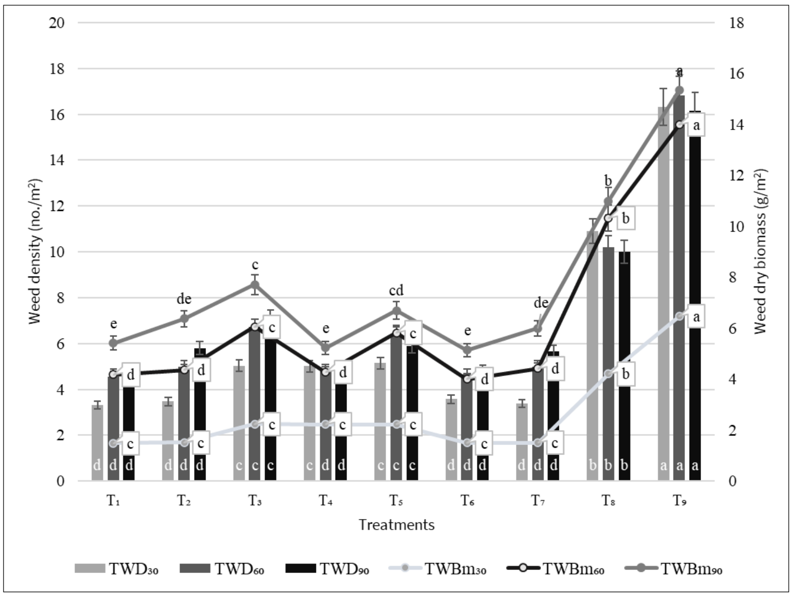


Fig. 3. Variations in weed menace under different IWM practices.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check; TWD Total weed density; TWBm Total weed dry biomass; 30, 60 and 90 – day of observation. Different alphabetical letters indicate significant differences within the parameter.

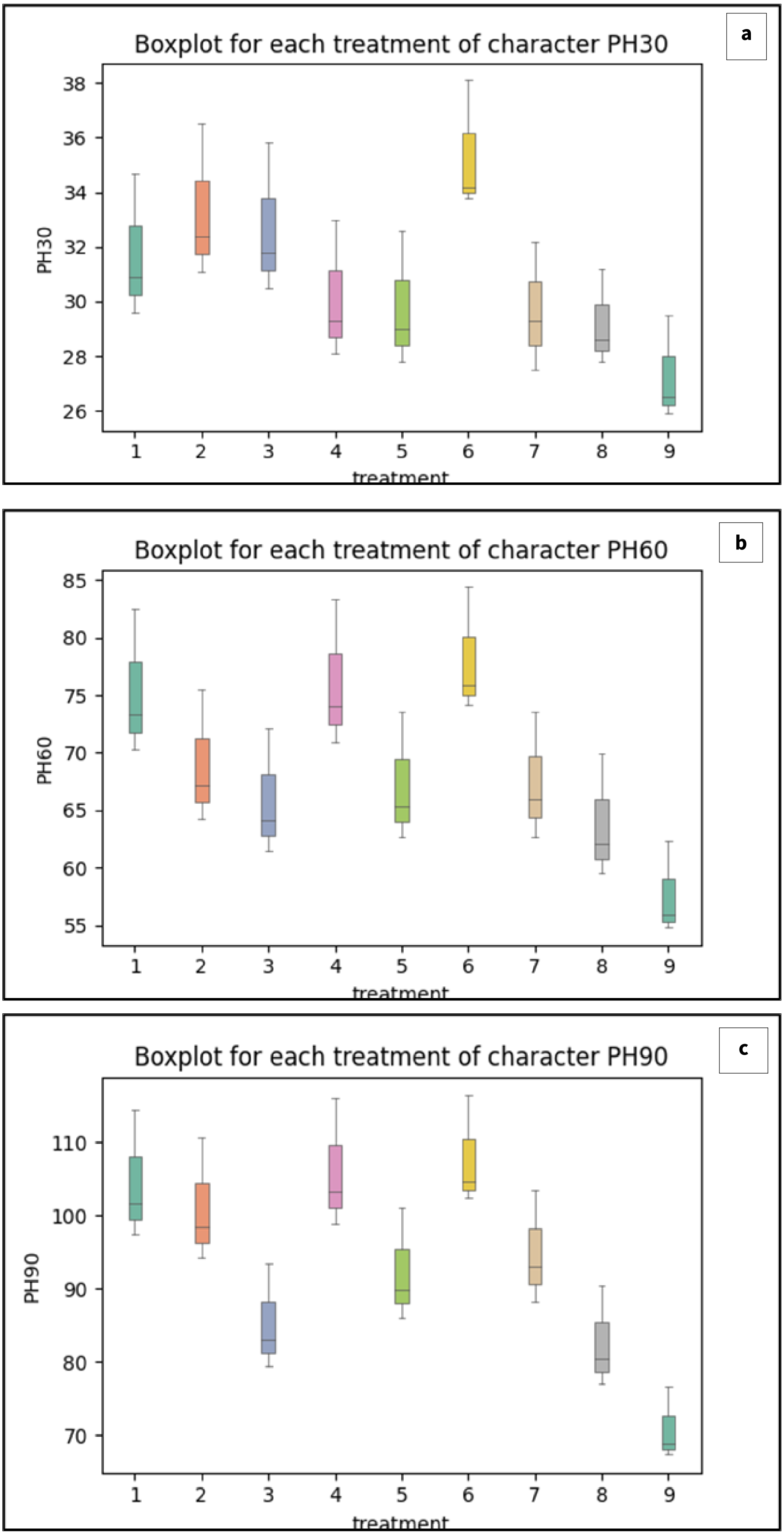


Fig. 4. Temporal variations in plant height (PH) at 30 (a), 60 (b) and 90 (c) DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check.

higher and on-par plant heights with the practice of PE PyrazE. *fb* EPoE Bispyr. *fb* one MW, that were ~1.31 times higher than the weedy check. However, the sole practice of two HW recorded the plant height (94.9 cm) that was comparable with the superior treatment, PyrazE. *fb* EPoE Bispyr. *fb* one MW (107.8 cm) at 90 DAS.

Plant dry biomass

Like plant height, the plant dry biomass was significantly superior in PE PyrazE. *fb* EPoE Bispyr. *fb* one MW, recording 64.8, 94.7 and 119.3 % higher biomass than weedy check at 30, 60 and 90 DAS respectively (Fig. 5). However, EPoE Bispyr. *fb* one HW recorded 77.1 % higher biomass than weedy check, which was on par with the superior practice of PE PyrazE. *fb* EPoE Bispyr. *fb* one MW (4303 kg/ha) at 60 DAS. Meanwhile, the sole practice of two HW recorded lesser dry biomass accumulation (-13 % over superior practice) at 90 DAS, which was on par with the sole practice of two MW. However, these two practices were significantly better than weedy check, producing approximately 89 % more plant dry biomass.

Number of tillers

All the evaluated IWM practices resulted in a significantly higher number of tillers/m^2 over the sole practice of two HW, two MW and weedy check at 30 DAS, thus indicating the need for integration of different weed management practices. The increase in the number of tillers/m^2 was significantly higher (+94, +202 and +213 no./m^2, over weedy check) under PE PyrazE. *fb* EPoE Bispyr. *fb* one MW at 30, 60 and 90 DAS respectively (Fig. 6). At 60 DAS, EPoE Bispyr. *fb* one HW and PE Pendi. *fb* two HW witnessed +174 and +173 number of tillers respectively higher than weedy check, which was essential for improving the number of productive tillers per plant. At 90 DAS, weedy check plots had only 185 tillers/m^2 incurring more than 50 % reduction due to weeds.

Leaf Area Index (LAI)

During the initial crop growth period (30 DAS), PE PyrazE *fb* EPoE Bispyr. *fb* one MW recorded significantly superior LAI over all other practices with the value of 0.95, while the lower value of 0.42 was recorded under weedy check (Fig. 7). However, EPoE Bispyr. *fb* one HW and PE Pendi. *fb* two HW also recorded above 3.5 LAI at 60 DAS and were on par with superior practice of PE PyrazE *fb* EPoE Bispyr. *fb* one MW (4.3 times LAI increment over weedy check). Even at 90 DAS, weedy check plots recorded significantly lower LAI that resulted in a decrement of 3.43 times than the plot with lowest weed infestation.

Nutrient uptake by crops

The nutrient uptake by rice crop varied significantly with weeds menace. In all the observations, the PE PyrazE.*fb* EPoE Bispyr. *fb* one MW recorded significantly higher nutrient uptake with 86.80, 20.84 and 79.37 kg/ha of N, P and K uptake respectively at 90 DAS (Fig. 8). All the other IWM practices along with the sole practice of two HW and two MW were significantly higher than weedy check that recorded 54.8, 53.9 and 51.73 % lower uptake of N, P and K respectively than the superior practice at 90 DAS.

Root parameters

The root parameters of aerobic rice *viz.*, root length, root biomass and root volume were recorded at 20, 30 and 40 DAS. The significant influence of different IWM practices was noticed at 40 DAS only, while no significant effect on root parameters was noticed at 20 and 30 DAS (Fig. 9). PE PyrazE *fb* EPoE Bispyr. *fb* one MW had significantly higher root length (+30 %), root biomass (~ +50 %) and root volume (more than double) than weedy check. All the weed management practices recorded non-significant variation with respect to rice root parameters, with PE PyrazE. *fb* two MW being the second superior practice.

Variation in yield attributes and yield of aerobic rice as influenced by different IWM practices

The variations in yield parameters and yield of aerobic rice are well expected as the growth parameters shown up and down regulations with different IWM practices. The number of panicle-bearing productive tillers were significantly higher under PE PyrazE *fb* EPoE Bispyr. *fb* one MW, that was at par with EPoE Bispyr. *fb* one HW, producing +193 and +171 more productive tillers per m^2 respectively than weedy check. The sole practice of two HW and two MW recorded 24.3 and 31.3 % lesser productive tillers than the superior practice (Table 5). The effective weed management under PE PyrazE *fb* EPoE Bispyr. *fb* one MW enhanced the panicle length (17.84 cm), panicle weight (1.88 g) and the total number of grains (99.33 no./panicle). The practice also resulted in a higher number of filled grains per panicle, which was 131 % higher than the weedy check, while the sole practice of two HW produced 80.7 % more filled grains per panicle. The better reduction in weed competition further improved the percentage of filled grains, which increased up to 88.5 % under the superior practice. However, different IWM practices did not produce any significant variations in the test weight of aerobic rice.

Table 5. Yield attributes and yield of aerobic rice under different IWM practices

Trt.	Productive tillers/m^2	Panicle length (cm)	Panicle weight (g)	No. of grains/ panicle	No. of filled grains/ panicle	Percent filled grains (%)	Test weight (g)	Grain yield (kg/ha)	Straw yield (kg/ha)
T_1	298.0	16.96	1.67	89.67	78.00	86.9	19.93	3314	4463
T_2	278.3	16.29	1.58	85.67	73.33	85.6	19.91	3251	4407
T_3	243.7	14.89	1.38	75.67	63.33	83.7	19.78	2999	4150
T_4	310.0	17.61	1.77	93.33	82.67	88.5	20.11	3502	4685
T_5	263.0	15.54	1.52	82.67	70.33	85.1	19.85	3111	4269
T_6	331.7	17.84	1.88	99.33	88.00	88.5	20.14	3544	4717
T_7	251.3	15.17	1.45	79.33	68.67	86.5	19.62	3095	4264
T_8	227.0	14.61	1.34	72.33	63.00	87.1	19.71	2978	4136
T_9	139.0	13.35	0.86	48.33	38.00	78.6	19.73	1498	2452

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check

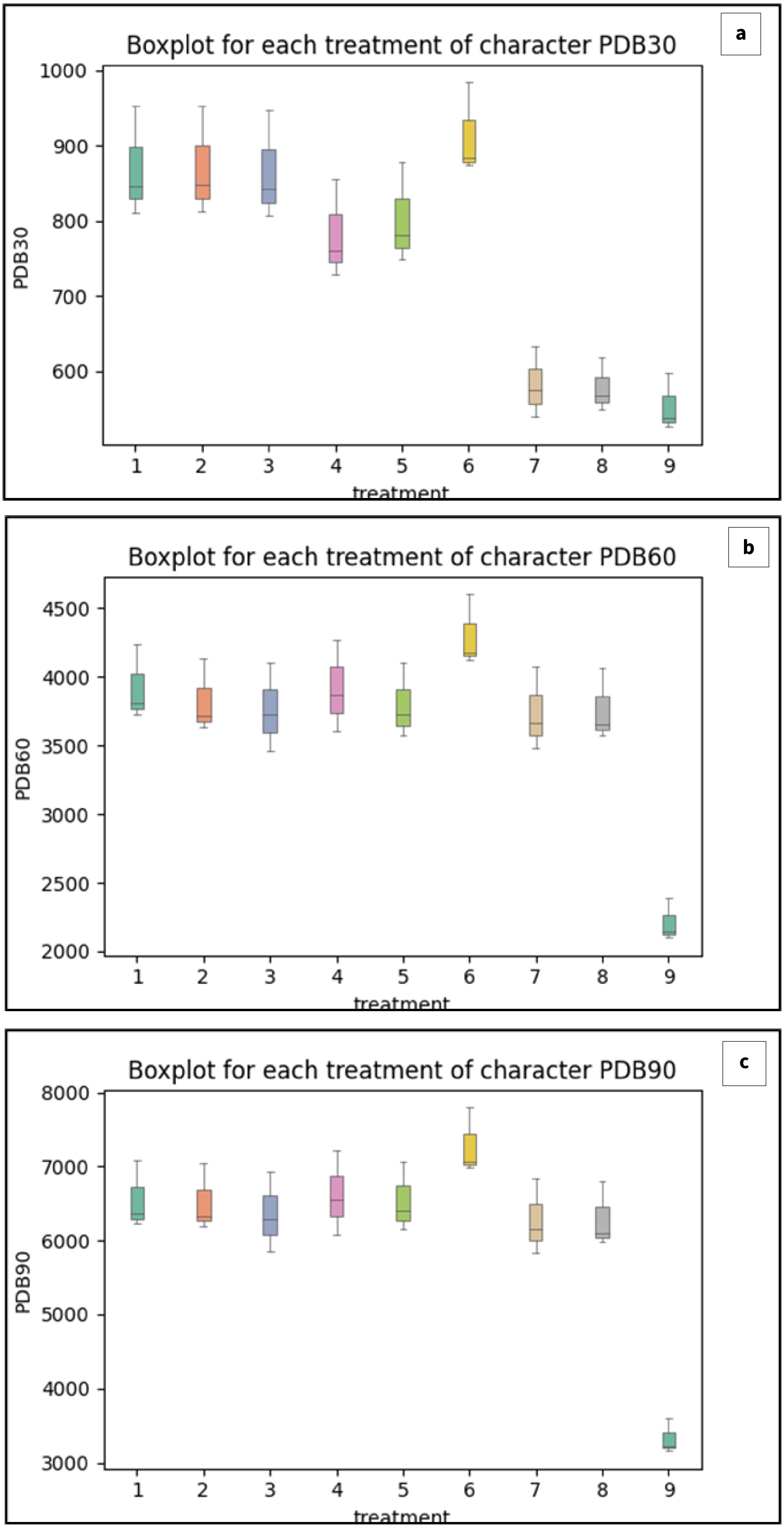


Fig. 5. Temporal variations in plant dry biomass (PDB) at 30 (a), 60 (b) and 90 (c) DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check.

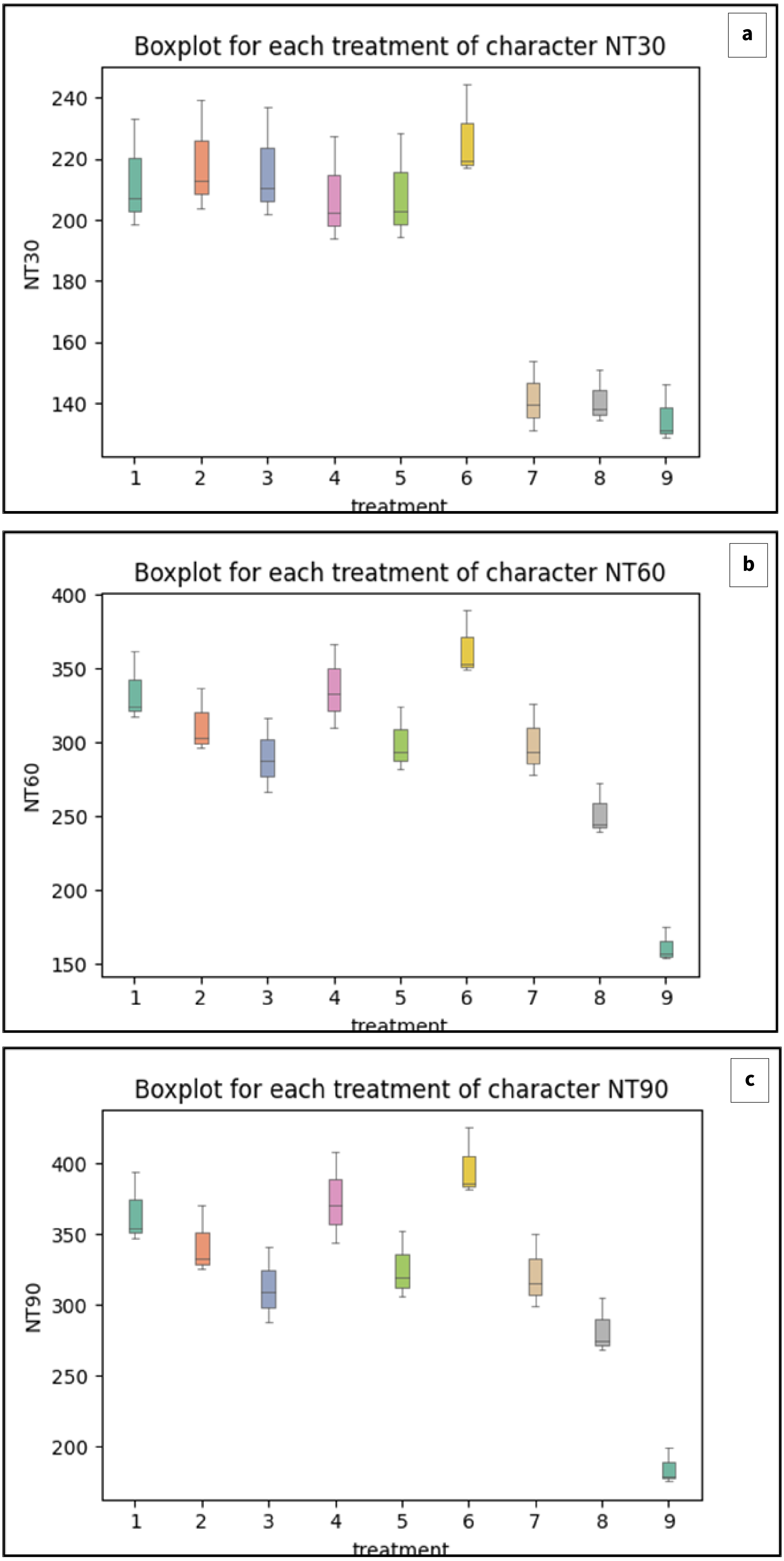


Fig. 6. Temporal variations in number of tillers per m2 (NT) at 30 (a), 60 (b) and 90 (c) DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check.

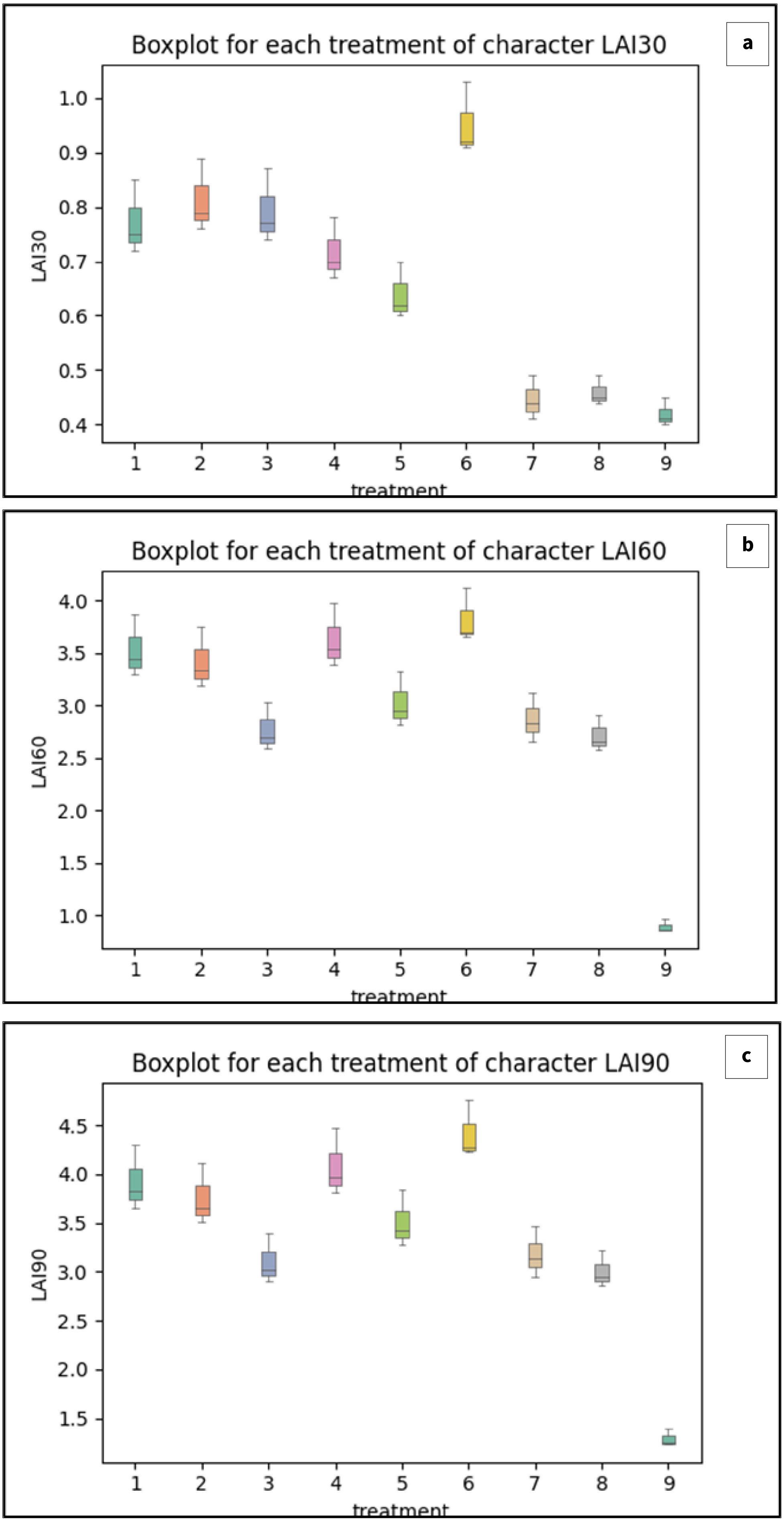


Fig. 7. Temporal variations in LAI at 30 (a), 60 (b) and 90 (c) DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check.

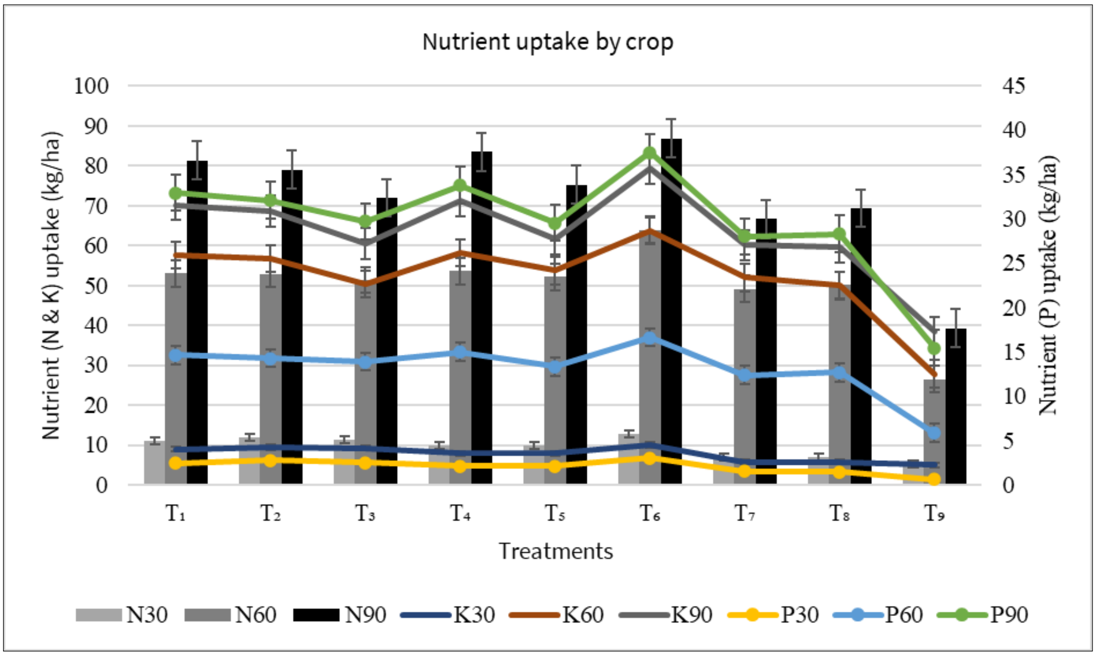
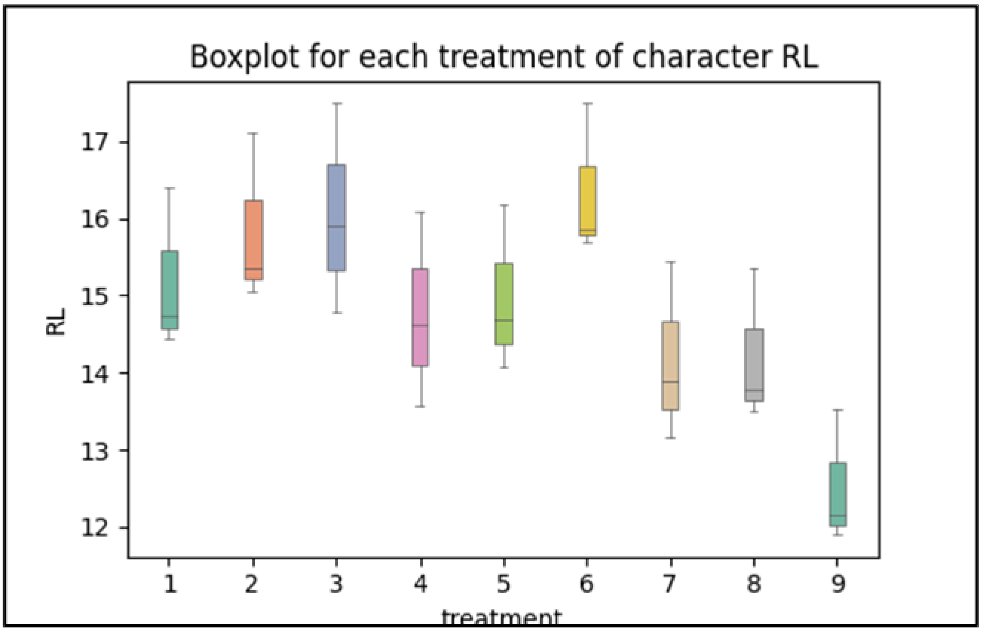
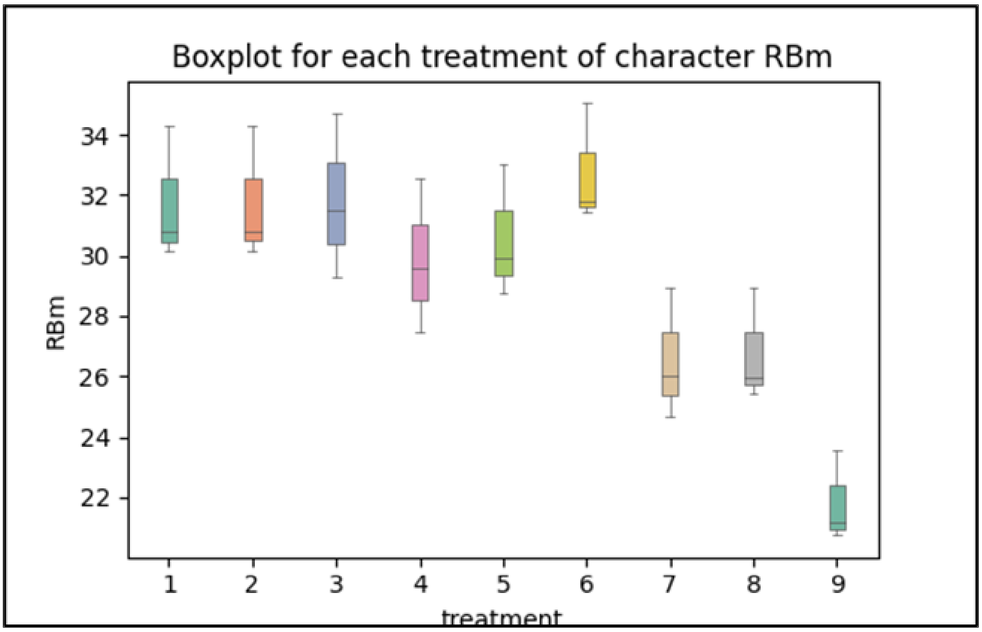


Fig. 8. Temporal variations in nutrient uptake (N, P and K) at 30, 60 and 90 DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check; N nitrogen; P Phosphorous; K potassium; 30, 60 and 90 – days after sowing.





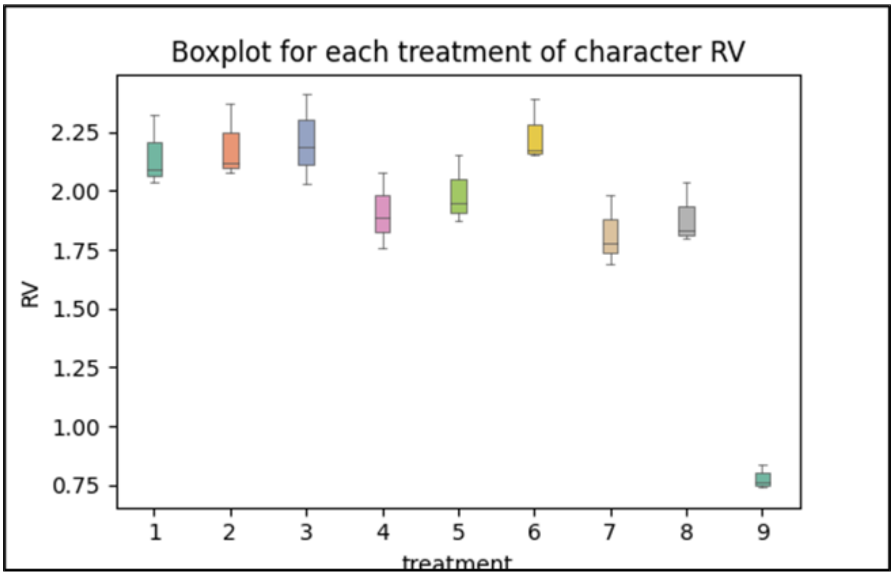


Fig. 9. Significant variations in root length (RL), root dry biomass (RBm) and root volume (RV) at 40 DAS.

T1 PE Pendi. *fb* two HW; T2 PE PyrazE. *fb* two HW; T3 PE PyrazE. *fb* two MW; T4 EPoE Bispyr. *fb* one HW; T5 EPoE Bispyr. *fb* one MW; T6 PE PyrazE. *fb* EPoE Bispyr. *fb* one MW; T7 Two HW; T8 Two MW; T9 Weedy check.

The aerobic rice yield got significantly uplifted under different IWM practices over weedy check. The better control of weeds under PE PyrazE *fb* EPoE Bispyr. *fb* one MW resulted in significantly higher yield of 3544 kg/ha (2.37 times that of weedy check), which was at par with EPoE Bispyr. *fb* one HW, that recorded1.33 times yield increment over the weedy check. Hence, proved that severe weed menace can reduce the aerobic rice yields by up to 57.7 % without any weed control measures.

Impact of different IWM practices on economics

The IWM practices carried under aerobic rice were found to improve the net returns by reducing the yield loss from weeds.PE PyrazE *fb* EPoE Bispyr. *fb* one MW recorded the highest net returns of ₹ 29244 per hectare, with B-C ratio of 1.84 (Table 6). The weedy check plots with reduced cost of cultivation and much lesser gross returns resulted in negative net returns with B-C ratio below 1.

Herbicide residues under different IWM practices

Among the three herbicides used under different IWM practices, pendimethalin was found to remain for longer duration. PE Pendi. was completely degraded by 60 days after herbicide spray (DAHS), as it was below detectable limit in soil (Table 7) whose initial concentration was 0.512 mg/kg. PE PyrazE sprayed at 3 DAS was almost degraded by 18 DAS (0.01 mg/kg). Similar observations were noted for the residue of EPoE Bispyr., which was sprayed on the 12th DAS. The initial bispyribac sodium residue in soil was 0.03 mg/kg and was below the detectable limit at 18 DAS.

Discussion

Variations in effect of different herbicides and their doses on phytotoxicity, seedling growth and weed menace under preliminary study

Current results indicated that Bispyr. at 50 g/ha exhibited stunted growth and chlorotic appearance in rice seedlings, though injury level varied with prevailing temperature. A previous study substantiates these findings. Similar trends were observed with dry biomass accumulation in rice (17). The mode of action for Bispyr. is the reduction or inhibition of acetolactate synthase (ALS) activity in plants (18). Bispyr. has reduced rice shoot biomass by 9 to 17 % compared to normal levels (19). Sharma et al. (20) predicted that the reduction in ALS inhibition is due to, either i) the enzyme inhibition complex formation that might have destabilized the enzyme, causing its degradation, ii) the irreversible and inactive enzyme inhibitor complex generation, or iii) the production of byproducts (intermediates) in the pathway of valine, leucine and isoleucine synthesis (21). Additionally, growth reduction may result from oxidative damage to the photosynthetic apparatus, leading to decreased chlorophyll and carotenoid contents in leaves (20, 22). The weed-controlling ability of the herbicides increased with increasing the herbicide dose, which might be due to higher reduction in acetolactate enzyme activity and associated branched-chain amino acid production (18) in weed plants. The present findings were in line with the results (23-25), where the application of herbicides resulted in down-regulation of enzyme activity and caused oxidative stress, that finally resulted in death of weed plants.

Table 6. Influence of different IWM practices on the economics of aerobic rice cultivation

Treatments		Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	B-C ratio
T_1	PE Pendi. *fb* two HW	37788	59656	21868	1.58
T_2	PE PyrazE. *fb* two HW	37122	58519	21397	1.58
T_3	PE PyrazE. *fb* two MW	34147	53990	19843	1.58
T_4	EPoE Bispyr. *fb* one HW	35627	63030	27403	1.77
T_5	EPoE Bispyr. *fb* one MW	33077	55997	22920	1.69
T_6	PE PyrazE. *fb* EPoE Bispyr. *fb* one MW	34552	63796	29244	1.85
T_7	Two HW	44147	55715	11568	1.26
T_8	Two MW	32672	53613	20941	1.64
T_9	Weedy check	29272	26964	-2308	0.92

Table 7. Herbicide residues in soil

Treatments		Herbicide	Herbicide residues (mg/kg)								
			0 DAHS	1 DAHS	3 DAHS	7 DAHS	15 DAHS	30 DAHS	45 DAHS	60 DAHS	75 DAHS
T_1	PE Pendi. *fb* two HW	Pendimethalin	0.512	0.458	0.355	0.288	0.197	0.109	0.075	0.021	BDL
T_2	PE PyrazE. *fb* two HW	Pyrazosulfuron ethyl	0.021	0.018	0.015	0.013	0.010	BDL	BDL	NA	NA
T_3	PE PyrazE. *fb* two MW	Pyrazosulfuron ethyl	0.022	0.020	0.017	0.012	0.010	BDL	BDL	NA	NA
T_4	EPoE Bispyr. *fb* one HW	Bispyribac sodium	0.030	0.027	0.021	0.018	0.013	BDL	BDL	NA	NA
T_5	EPoE Bispyr. *fb* one MW	Bispyribac sodium	0.026	0.023	0.018	0.016	0.012	BDL	BDL	NA	NA
T_6	PE PyrazE. *fb* EPoE Bispyr. *fb* one MW	Pyrazosulfuron ethyl	0.020	0.017	0.015	0.012	0.011	BDL	BDL	NA	NA
		Bispyribac sodium	0.027	0.024	0.020	0.018	0.012	BDL	BDL	NA	NA

NA not analyzed; BDL below detection limit; DAHS days after herbicide application

Temporal variations in weed menace under main field experiment

The initial reduction in weed density with IWM practices involving PE herbicides was due to the herbicide application at 3 DAS that prevented weed seed germination and emergence. However, the HW on 25th day played a major role in reducing the further weed growth in these treatments. The effectiveness of PE herbicides for initial weed control was studied and found out that the herbicides kept the field weed -free in the first two weeks of crop growth (26, 27). The later emerged weeds were effectively controlled by EPoE herbicides, that cleared the weeds preferably during critical crop weed competition period of 15 to 45 DAS. The efficiency of sequential application of PE PyrazE. and EPoE Bispyr. *fb* one MW or EPoE Bispyr. prior to one HW over the weed control has been documented (8, 28, 29). Even though 45th day HW was commonly carried for PE Pendi. *fb* two HW; EPoE Bispyr. *fb* one HW and sole practice of two HW, weed density and weed dry matter kept on increasing under the sole practice of two HW, while the practices involving herbicide spray decreased the weed growth rate. This might be attributable to the residual nature of herbicides in the soil that would have rendered longer periods of weed control (30). The MW practiced either after application of PE PyrazE.or without any herbicide was found very less effective in controlling the weeds, as the overall weed control efficiency was 80.84 and 61.69 % respectively. However, the difference between them can be directly attributed to the inclusion of one PE herbicide spray, that increased the weed control efficiency by reducing the weed density up to 56.7 %. However, the MW carried out after the application of PE PyrazE. and EPoE Bispyr. had significantly reduced the weed density and weed dry biomass, with overall weed control efficiency and weed control index of 91.91 and 89.01 % respectively. This indicated the residual control effect of chemical herbicide, which might have reduced the emergence and establishment of new weeds (reducing weed density) and curbed the growth rate of leftover weeds (reducing weed dry biomass).

Variation between weed density and weed dry biomass

From the correlation data, the weed density and dry matter accumulation in weeds were strongly correlated with a positive magnitude of 0.99, indicating the increase of accumulated dry matter in weeds for an increase in the weed population. A correlation value of 0.98 has been obtained for the relationship between weed density and weed dry matter (28).The weedy plots with higher number of weeds per unit area, simultaneously recorded higher dry matter accumulation in weeds. From the current research data, it was also found that the order of treatments for increasing weed dry biomass did not follow the same order as that of weed density. The weed density and weed dry biomass value respectively follows the sequence: at 30 DAS - T_1< T_7< T_2< T_6 and T_1< T_6< T_7< T_2; at 60 DAS - T_1< T_6< T_4 and T_6< T_1< T_4. The weeds in few numbers that remained after the treatment imposition (under HW i.e., in T_7 and T_2) accumulated comparatively higher dry matter than the new weeds that emerge once after the treatment effect subsides (under T_6). The site where weeds were left also played a role. The weeds in inter-row may accumulate more dry matter than those left in the intra-row spaces (in rectangular spacing of 20 x 10 cm), because of less competition from crops and greater space, nutrients and moisture availability in the inter-row than the intra-row. Between the two better performing treatments, though higher weed density was noticed in the treatment of PE PyrazE. *fb* EPoE Bispyr. *fb* one MW (T_6) than the treatment of PE Pendi. *fb* two HW (T_1) at 60 DAS, the weeds that remained after 45th day MW in the intra-row (under T_6) accumulated lesser dry matter than those remained in inter-row after the 45th day HW (under T_1). The order of treatments for increasing dry matter did not coincide with that of the order for weed density (31). Comparatively higher weed density was found in herbicide treated (at 3 - 5 DAT) plots than the hand weeded plots, but weed dry matter was recorded higher in the latter at 20 DAT (31). The new weeds may account for higher weed density, but the higher dry matter will be accumulated in those which remained unaffected by the imposed treatment. Moreover, the weeds remained in herbicide treated plots might have reduced growth rate due to their exposure to herbicide spray. In the meantime, the weeds left by chance under HW might show higher growth rate and hence more dry biomass accumulation. In chickpea crop, the same values (45 no./m^2) were recorded for the two weed density treatments, while a variation of 5.5 g/m2 in the weed dry matter accumulation (32). Hence the perfect correlation between the weed density and weed dry matter can't be obtained, even though in general weed dry matter increases with weed density. Between weed density and weed dry matter, the correlation expressed was less than one (33- 36).

Temporal variation in aerobic rice performance

Different IWM practices had varied control over aerobic rice growth. The response was clearly higher in those practices that controlled the weeds mainly during critical period of crop-weed competition i.e., between 15 and 45 DAS for aerobic rice. PE PyrazE. *fb* EPoE Bispyr. *fb* one MW witnessed increased aerobic rice growth over other IWM practices, which was mainly due to the sequential application of PE

PyrazE at 3 DAS and EPoE Bispyr. at 12 DAS that reduced the weed menace preferentially during the critical competition period (37). Aerobic rice should be kept weed-free between 21 and 43 DAS, to achieve better growth (38). The same effect was seen under the IWM practice of EPoE Bispyr. *fb* one HW. The reduction in weed dry biomass accumulation during critical period was the main reason for increasing the resource availability to the rice plant, thus increasing their growth at 60 DAS.

A negative relation was observed in between the plant height and weed dry biomass, which was reflected by the correlation values (Fig. 10). Aerobic rice is susceptible to weeds since the first day of its life cycle (39). The reduced plant dry biomass under weedy check indicated the need for PE herbicide for initial weed control (35). The practices involving PE herbicide application successfully controlled the weed menace and increased the growth at 30 DAS. However, the increased biomass in rice plants under the practice of EPoE Bispyr. *fb* one HW over PE PyrazE. *fb* two HW and PE PyrazE. *fb* two MW at 60 DAS was due to the higher PyrazE. *fb* two HW and PE PyrazE. *fb* two MW respectively. Thus, one herbicide spray at 12 DAS can increase the available resources for crop during the critical period and increase the crop growth rate, which can even surpass the performance of crop grown under PE spray. Similar observations were made (40) on the relation between weed-prone periods and dry-seeded rice growth and yield, where they found that PR-114 rice cultivar needed longer duration of weed free periods (1.8-83.2 days), while PR-115 cultivar required comparatively lesser (17.1-57.4 days), to achieve higher yields. The plant biomass enhancement can also be seen under the sole practice of two HW which were done on 25th and 45th DAS. The 25th day HW provided weed-free condition mainly during the critical period, which increased the crop performance as witnessed by higher biomass at 60 DAS.

The number of tillers per plant indicating flexibility of crops under stress-free conditions, increased between 30 and 60 DAS due to weed control either by EPoE spray or the physical removal of weeds. EPoE Bispyr. *fb* one HW and the sole practice of two HW clearly demonstrated the increased number of tillers as well as leaf area index from 30 to 60 DAS. The earlier studies (41, 42) also validate the present findings, pertaining to effect of integrated weed management on productive tillers, where the numbers got improved from 4.8 under unweeded control, to 8.6 under integrated practice of pendimethalin fb hand weeding. Hence, there lies a flexibility in crop growth that can be exploited positively by controlling the weed menace preferentially at critical crop-weed competition period. Additionally, the crop benefitted from improved nutrient uptake that was necessary for photosynthates production. The herbicide application leads to a higher nutrient uptake by the crop owing to less weed menace (43). PE PyrazE. *fb* EPoE Bispyr. *fb* one MW had higher nutrient content in rice plants, due to lesser competition from weeds and more nutrient uptake at all the stages. The significant variations noted for root parameters at 40 DAS as against weedy check was another indication of the positive impact of IWM practices towards crop performance at critical periods. Though, the PE herbicides controlled the weeds and improved the above-ground parameters by 30 DAS, the below-ground parameters were not significantly affected during that observation. However, the 12thday spray of EPoE herbicide and 25thday operations like physical removal of weeds were found to impart significant variations in root growth. The practices with MW at 25th DAS had comparatively higher values at 40 DAS, which might be due to soil disturbance with the mechanical weeder that increased the soil aeration and hence root respiration. MW has benefits on rice growth and yield (44). Overall, we can infer from the growth data that there was a positive outcome with aerobic rice performance under different IWM practices that can be clearly attributed to reduced weed competition mainly during the critical period of crop-weed competition.

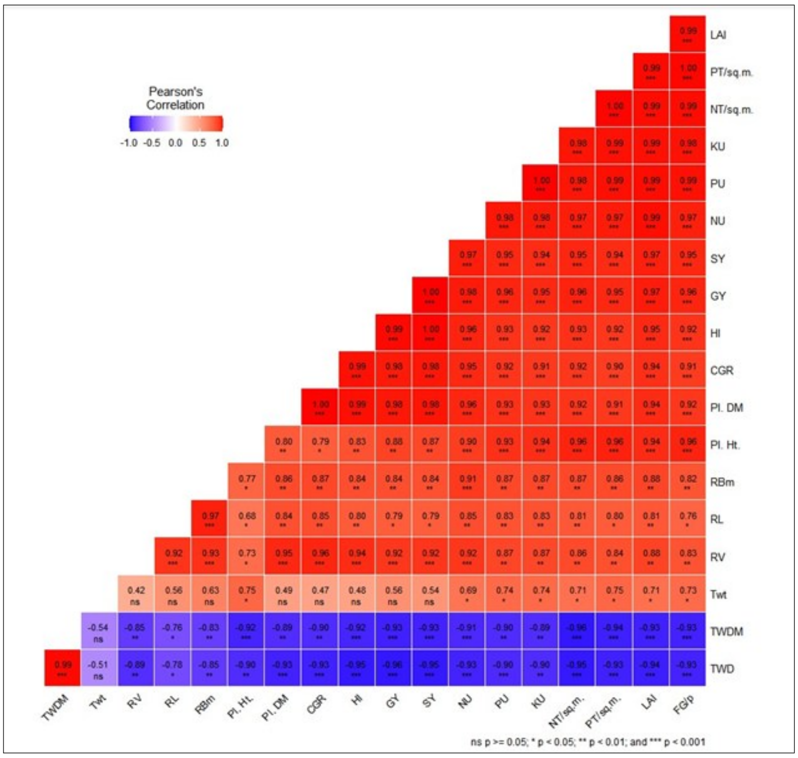


Fig. 10. Correlation between weed and crop parameters.

The aerobic rice performance was upregulated for yield attributes that ultimately reflected on total grain and straw yield. The increased growth parameters like plant height, biomass accumulation, leaf area index and tillers number per plant have eventually enhanced the yield-determining characteristics like productive tillers, filled grains, etc. The increase in total number of tillers per plant and the photosynthate accumulation in plants supported a higher number of productive tillers. The translocation and accumulation of synthesized photochemical products from vegetative portion to grains might have enhanced the competition-free environment, which was ensured by PE PyrazE. *fb* EPoE Bispyr. *fb* one MW from the sowing to till harvest of the crop. The weed menace under weedy check clearly indicated the indirect competition imposed by weeds on crop that affect the reproductive stages by reducing the panicle-related attributes like panicle length, panicle weight and number of grains per panicle by 25.2, 54.25 and 51.33 % respectively. However, PE PyrazE. *fb* EPoE Bispyr. *fb* one MW provided better weed control at critical periods, which improved the crop performance and ensured higher yields of aerobic rice. Similar results were also obtained (45-47).

Impact on economics

The IWM practices might appear to be costly as they involve the combination of more than one practice. But with the inclusion of chemical herbicides, the cost incurred for labour wages can be effectively reduced. In comparison to the sole practice of two HW, all the IWM practices recorded lesser cost of cultivation. Even after including a PE spray, the practice of PE PyrazE. *fb* two HW had lesser cost of cultivation due to the lesser labour usage for weed removal, as the initial flush was controlled by pre-emergent spray. Also, the inclusion of MW instead of HW further reduced the cost of the weed management practice. The practice of PE PyrazE. *fb* EPoE Bispyr. *fb* one MW had higher net returns, which was mainly due to higher yields achieved with less weed competition. Higher net returns and B-C ratio were obtained with sequential herbicide application under the integrated approach (41, 48, 49). However, the absence of any weed control practices under weedy check recorded negative net returns due to 57.7 % reduction in yield, even though the cost of cultivation was low. A similar B-C ratio for weedy check was reported, where weedy check recorded 0.73, while the integration of pre-emergent herbicide, pendimethalin with manual weeding recorded higher B-C ratio of 1.28 (50).

Low residue herbicides under IWM practices

The values pertaining to post harvest herbicide sprayed in soil samples indicated that the herbicides were below detectable limits at 15 DAHS, i.e., at 18 DAS for pyrazosulfuron ethyl and 27 DAS for bispyribac sodium. This explained their efficacy period for weed control under aerobic rice, after which the new weeds may emerge and affect the crop. Notably this duration falls between the critical period of crop weed competition for aerobic rice i.e., 15 to 45 DAS. Thus, there is a need to integrate HW and MW practices with these herbicide applications to ensure lower weed density at critical periods. A faster dissipation of pyrazosulfuron ethyl in soil was noted, with 90 % of herbicide dissipated within 40 days of application (51). Within the first 5 days of herbicide application, more than 90 % of bispyribac sodium has been dissipated (52). From the present research, it was also proved that the higher efficiency of weed control can be ensured by mere supplementation with physical removal methods for pre- and early-post emergent herbicides. Simultaneously, less herbicide residue retention might give more choices for early as well as successful establishment of succeeding crops and ensure environmental safety.

Conclusion

Aerobic rice, grown in upland conditions, has suffered severe competition from weeds since the first day. The overall growth reduction in crops was clearly due to weeds that imposed indirect competition for light, nutrients, space and moisture. Though the individual practices were proven to reduce weed infestation, the IWM practices were found to curb the weed growth preferentially at the critical period of competition. The practice of PE PyrazE. *fb* EPoE Bispyr. *fb* one MW ensured a weed-free situation from the beginning up to harvest, as it included pre-emergent and early-post emergent herbicides integrated with MW. The aerobic rice performance was enhanced holistically with 2.36 times more yield than weedy conditions, incurring a total net return of ₹ 29244 per hectare. Additionally, pyrazosulfuron ethyl and bispyribac sodium were found to be faster degrading, which provides residue-free soil conditions for subsequent crops.

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Authors' contributions

The processes of conceptualization, methodological design and validation were done by DJK, SR and PMA. DJK, SR, MA and VFV have conducted the analysis and curation of the data. DJK, NP, BMN and GMVG composed the original draft paper. DJK, NP, BMN and GMVG conducted the review and editing. DJK, SR and PMA executed the supervision.

Compliance with ethical standards

Conflict of interest: The authors have no competing interests to declare that are relevant to the content of this article.

Ethical issues: None

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