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INFLUENCE OF SEQUENTIAL WEED MANAGEMENT PRACTICES ON POST-HARVEST SOIL PROPERTIES AND ECONOMIC SUSTAINABILITY IN WET DIRECT-SEEDED RICE (*Oryza sativa* L.)

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ABSTRACT

A field experiment was conducted during the *kharif* season of 2025 at the Instructional-cum-Research Farm, Assam Agricultural University, Jorhat, Assam, to evaluate the influence of sequential weed management practices on post-harvest soil properties and economic sustainability in wet direct-seeded rice. The experiment was laid out in a randomized complete block design with ten weed management treatments and three replications. Weed management practices significantly influenced weed biomass, nutrient uptake by weeds, post-harvest available soil nutrients and economic returns, whereas bulk density, soil pH, electrical conductivity, organic carbon and soil microbial biomass carbon remained unaffected. Pretilachlor 30% + Pyrazosulfuron ethyl 0.75% WG @ 615 g ha⁻¹ as pre-emergence followed by Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC @ 150 g ha⁻¹ as PoE (T₃) recorded the lowest weed dry weight (34.33 g m⁻²) and nutrient uptake by weeds (4.07 kg N, 1.49 kg P and 4.62 kg K ha⁻¹), resulting in higher post-harvest available nitrogen (240.20 kg ha⁻¹), phosphorus (20.00 kg ha⁻¹) and potassium (122.27 kg ha⁻¹). The same treatment also recorded the highest net return (₹87,904 ha⁻¹) and benefit-cost ratio (1.98) among the weed management practices. Correlation analysis further indicated that reduced weed biomass was closely associated with improved residual soil nutrient status, higher grain yield and enhanced profitability. The results indicate that Pretilachlor 30% + Pyrazosulfuron ethyl 0.75% WG @ 615 g ha⁻¹ as pre-emergence followed by Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC @ 150 g ha⁻¹ as PoE is an effective and economically sustainable weed management strategy for wet direct-seeded rice under the agro-climatic conditions of Assam.

Key words : Wet direct-seeded rice, Sequential herbicides, Post-harvest soil fertility, Nutrient conservation, Economic returns.

Introduction

Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population and plays a vital role in ensuring food security in India. Increasing labour scarcity, rising production costs and limited water availability have promoted the adoption of direct-seeded rice (DSR) as an alternative to conventional transplanted rice because of its lower labour and water requirements and greater scope for mechanization (Gopal *et al.*, 2019;

Dey *et al.*, 2024).

Despite its advantages, weed infestation is the major biological constraint in wet direct-seeded rice, where simultaneous emergence of rice and weeds results in severe competition for nutrients, moisture, light and space, leading to considerable yield losses (Abbas *et al.*, 2019; Singh *et al.*, 2019). Weeds also remove substantial amounts of nitrogen, phosphorus and potassium from the soil, thereby reducing nutrient availability to the crop and

fertilizer-use efficiency (Pooja *et al.*, 2021).

Sequential application of pre- and post-emergence herbicides has emerged as an effective strategy for season-long weed control in direct-seeded rice. Such programmes provide broad-spectrum weed control, reduce nutrient depletion by weeds and improve crop productivity and profitability compared with single herbicide applications (Abbas *et al.*, 2019). Integration of herbicides with mechanical or manual weeding further enhances weed management and economic returns (Dhakal *et al.*, 2019).

Besides improving weed control, effective weed management contributes to nutrient conservation and influences post-harvest soil fertility. Assessment of post-harvest soil properties and economic returns provides valuable information on the sustainability of different weed management strategies (Pooja *et al.*, 2021; Sarma *et al.*, 2024). However, information on the combined influence of sequential weed management practices on post-harvest soil properties and economic sustainability in wet direct-seeded rice under the agro-climatic conditions of Assam is limited.

Therefore, the present study was undertaken to evaluate the influence of sequential weed management practices on post-harvest soil properties and economic sustainability in wet direct-seeded rice.

Materials and Methods

Experimental site

A field experiment was conducted during the *kharif* season of 2025 at the Instructional-cum-Research Farm,

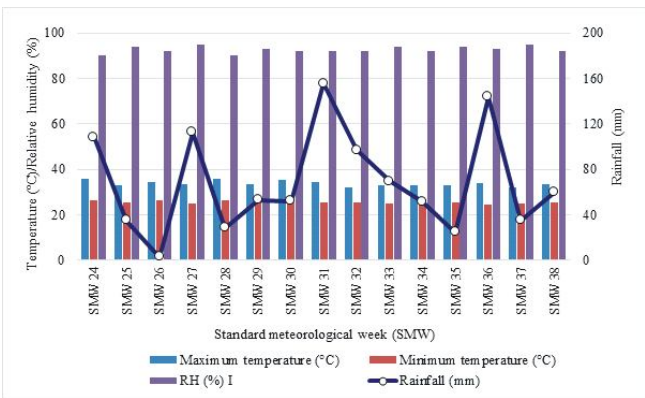


Fig. 1 : Weekly meteorological parameters recorded during the experimental period (*kharif*, 2025) at the Instructional-cum-Research Farm, Assam Agricultural University, Jorhat, Assam (SMW 24 = 11 June - 17 June).

Assam Agricultural University, Jorhat, Assam, India (26°45' N, 94°12' E; 87 m above mean sea level). The experimental soil was sandy loam with pH 5.20, EC 0.18 dS m⁻¹, bulk density 1.39 Mg m⁻³, organic carbon 0.65%, available N 290.5 kg ha⁻¹, available P₂O₅ 21.8 kg ha⁻¹, available K, O 140.2 kg ha⁻¹ and soil microbial biomass carbon (SMBC) 223.5 µg C g⁻¹ soil. Weekly meteorological data recorded during the crop growing period are presented in Fig. 1.

Experimental design and crop management

The experiment was laid out in a Randomized Complete Block Design (RCBD) with ten weed management treatments and three replications. Wet direct-seeded sali rice (*Oryza sativa* L.) cv. Arun was sown at 20 cm row spacing using a seed rate of 35 kg ha⁻¹. A recommended fertilizer dose of 60:20:40 kg

Table 1 : Initial physico-chemical properties of soil.

S. no.	Constituents	Value	Interpretation	Method of analysis
1	Mechanical fraction (%)			
	Sand	65.59	Sandy loam	International Pipette Method (Piper, 1966)
	Silt	14.89		
	Clay	19.52		
2	Bulk density (Mg/m ³)	1.39	-	Core sampler method (Bodman, 1942)
3	Soil pH	5.2	Acidic	Glass electrode pH meter (1:2.5) (Jackson, 1973)
4	Electrical conductivity (dS m ⁻¹)	0.18	Non-saline	Conductivity meter (Jackson, 1973)
5	Soil organic carbon (%)	0.65	Medium	Walkley and Black wet oxidation method
6	Available N (kg ha ⁻¹)	290.5	Medium	Alkaline permanganate method (Subbiah and Asija, 1956)
7	Available P ₂ O ₅ (kg ha ⁻¹)	21.8	Low	Brays I method (Jackson, 1973)
8	Available K ₂ O (kg ha ⁻¹)	140.2	Medium	Flame photometric method (Jackson, 1973)
9	Soil microbial biomass carbon (µg C g ⁻¹ soil)	223.5	-	Chloroform fumigation-extraction method (Vance <i>et al.</i> , 1987)

$\text{N:P}_2\text{O}_5 : \text{K}_2\text{O ha}^{-1}$ was applied. Pre-emergence herbicides were applied at 2 DAS, whereas post-emergence herbicides were applied at 25 DAS using a knapsack sprayer fitted with a flat-fan nozzle. Mechanical and manual weeding were carried out as per the treatment schedule, while all other recommended agronomic practices were followed uniformly.

Soil sampling and laboratory analysis

Composite post-harvest soil samples (0-15 cm depth) were collected from each experimental plot after harvest and analysed for bulk density, pH, EC, organic carbon, available N, available P_2O_5 , available K_2O and SMBC using standard analytical procedures (Table 1). Weed dry weight was recorded at harvest from a $0.5 \text{ m} \times 0.5 \text{ m}$ quadrat and nutrient uptake (N, P and K) by weeds was computed from nutrient concentration and weed dry weight. Grain yield and economic parameters, viz., cost of cultivation, gross return, net return and benefit-cost ratio, were calculated using prevailing input and output prices.

Statistical analysis

The data were analysed by analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design. Treatment means were compared using the critical difference (CD) test at $P = 0.05$. Pearson's correlation analysis was performed to study the relationships among weed biomass, nutrient uptake by weeds, post-harvest soil nutrient status, grain yield and economic parameters.

Results and Discussion

Weed biomass and nutrient removal by weeds

Weed management practices significantly influenced weed dry weight production and nutrient uptake by weeds at harvest (Table 2). In the weed-free treatment (T_{10}), weed growth was completely suppressed and consequently no nutrient removal by weeds was recorded. Among the weed management treatments, the sequential application of Pretilachlor 30% + Pyrazosulfuron ethyl 0.75% WG @ 615 g ha^{-1} as PE followed by Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC @ 150 g ha^{-1} as PoE (T_3) recorded the lowest weed dry weight (34.33 g m^{-2}) and nutrient uptake by weeds (4.07 kg N , 1.49 kg P and $4.62 \text{ kg K ha}^{-1}$). In contrast, the weedy check (T_9) recorded the highest weed dry weight (189.74 g m^{-2}) and nutrient uptake (24.92 kg N , 9.48 kg P and $27.14 \text{ kg K ha}^{-1}$), indicating severe crop-weed competition under the absence of weed control.

The superior performance of T_3 was attributed to

the complementary action of the pre-emergence and post-emergence herbicides, which effectively controlled successive flushes of grasses, sedges and broad-leaved weeds throughout the crop growth period. Pretilachlor + Pyrazosulfuron -ethyl provided effective early-season weed control, while the subsequent application of Florpyrauxifen-benzyl + Cyhalofop-butyl extended weed suppression during later growth stages, thereby minimizing weed biomass and nutrient removal. Similar reductions in weed dry weight with Pretilachlor + Pyrazosulfuron -ethyl have been reported by Yadav *et al.* (2018). Likewise, Kaur *et al.* (2025) observed that post-emergence application of Florpyrauxifen-benzyl + Cyhalofop-butyl effectively controlled complex weed flora and reduced weed biomass in direct-seeded rice. Reduced nutrient uptake by weeds under the sequential herbicide programme indicates more efficient utilization and conservation of nutrients for crop growth, which contributed to the higher post-harvest soil nutrient status observed in the present investigation.

Post-harvest soil properties

Weed management practices had no significant effect on post-harvest bulk density, soil pH, electrical conductivity (EC), organic carbon and soil microbial biomass carbon (SMBC) (Table 3). Bulk density ranged from 1.34 to 1.40 Mg m^{-3} , soil pH from 5.12 to 5.25 , EC from 0.16 to 0.21 dS m^{-1} , organic carbon from 0.64 to 0.65% , and SMBC from 221.90 to $225.83 \text{ } \mu\text{g C g}^{-1} \text{ soil}$. The absence of significant variation indicates that the weed management practices evaluated during a single cropping season did not alter these relatively stable soil properties. Herbicide application at the recommended doses also did not adversely affect soil microbial biomass, suggesting that the tested weed management practices were biologically safe under the prevailing soil conditions. Similar observations were reported by Pooja *et al.* (2021) and Sarma *et al.* (2024), who found that recommended herbicide-based weed management practices had little influence on soil physico-chemical properties and microbial activity after a single cropping season.

In contrast, post-harvest available nitrogen, phosphorus and potassium were significantly influenced by the weed management treatments (Table 3). The weed-free treatment recorded the highest available nitrogen ($242.00 \text{ kg ha}^{-1}$), phosphorus (20.00 kg ha^{-1}) and potassium ($126.00 \text{ kg ha}^{-1}$). Among the weed management treatments, T_3 maintained the highest residual nitrogen ($240.20 \text{ kg ha}^{-1}$), phosphorus (20.00 kg ha^{-1}) and potassium ($122.27 \text{ kg ha}^{-1}$), whereas the weedy check recorded the lowest values (203.00 , 17.00 and

Table 2 : Effect of sequential weed management practices on weed dry weight and nutrient uptake by weeds at harvest.

Treatments	Weed dry weight (g m ⁻²)	N uptake (kg ha ⁻¹)	P uptake (kg ha ⁻¹)	K uptake (kg ha ⁻¹)
T₁ : Pendimethalin 38.4% + Pyrazosulfuron ethyl 0.85% ZC 785 g/ha as PE <i>fb</i> Bispyribac-sodium 25 g/ha + [(Metsulfuron methyl + Chlorimuron ethyl) (RM)] 4 g/ha (Tank mix) as PoE at 25 DAS	44.37	5.55	2.00	6.05
T₂ : Penoxsulam + Pendimethalin (RM) 625 g/ha as PE <i>fb</i> Fenoxaprop-ethyl 67 g/ha + Ethoxysulfuron 18 g/ha (Tank-mix) as PoE at 25 DAS	38.67	4.86	1.81	5.36
T₃ : Pretilachlor 30.0% + Pyrazosulfuron ethyl 0.75% WG 615 g/ha PE <i>fb</i> Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC 150 g/ha as PoE at 25 DAS	34.33	4.07	1.49	4.62
T₄ : Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC 150 g/ha as PoE at 25 DAS	69.00	8.36	3.02	8.88
T₅ : Florpyrauxifen-benzyl 2.13%+Cyhalofop-butyl 10.64% EC 150 g/ha as PoE at 25 DAS <i>fb</i> mechanical weeding through paddy weeder at 40 DAS	57.07	6.65	2.38	7.60
T₆ : Pretilachlor 30.0% + Pyrazosulfuron ethyl 0.75% WG 615 g/ha PE <i>fb</i> mechanical weeding through paddy weeder at 40 DAS	55.67	6.34	2.22	7.34
T₇ : Pyrazosulfuron 20 g/ha PE <i>fb</i> Bispyribac-sodium 25 g/ha 25 DAS <i>fb</i> hand weeding at 40 DAS	40.01	4.60	1.64	5.32
T₈ : Mechanical weeding through paddy weeder at 20 and 40 DAS	71.17	9.21	3.52	9.99
T₉ : Weedy check	189.74	24.92	9.48	27.14
T₁₀ : Weed free check	0.00	0.00	0.00	0.00
S. Em (±)	0.41	0.43	0.17	0.48
CD (P=0.05)	1.23	1.27	0.51	1.41

Table 3 : Effect of sequential weed management practices on post-harvest soil properties.

Treatments	Bulk density (Mg m ⁻³)	pH	EC (dS m ⁻¹)	Organic carbon (%)	SMBC (µg C g ⁻¹ soil)	Available N (kg ha ⁻¹)	Available P ₂ O ₅ (kg ha ⁻¹)	Available K ₂ O (kg ha ⁻¹)
T ₁	1.38	5.19	0.18	0.64	223.43	233.07	19.33	118.07
T ₂	1.39	5.17	0.18	0.65	222.97	236.33	19.67	119.53
T ₃	1.37	5.23	0.17	0.65	224.13	240.20	20.00	122.27
T ₄	1.39	5.20	0.18	0.64	222.73	220.00	18.50	116.00
T ₅	1.36	5.21	0.17	0.65	224.73	225.67	18.80	117.23
T ₆	1.37	5.19	0.18	0.64	224.00	230.67	19.00	117.00
T ₇	1.35	5.15	0.17	0.65	225.03	238.20	19.73	118.97
T ₈	1.34	5.18	0.16	0.65	225.43	214.33	18.40	115.17
T ₉	1.40	5.12	0.21	0.64	221.90	203.00	17.00	107.00
T ₁₀	1.34	5.25	0.16	0.65	225.83	242.00	20.00	126.00
S. Em (±)	0.06	0.18	0.01	0.02	6.06	6.25	0.53	3.14
CD (P=0.05)	NS	NS	NS	NS	NS	18.56	1.57	9.34

Table 4 : Effect of sequential weed management practices on economics of wet direct-seeded rice.

Treatments	Cost of cultivation (₹ ha ⁻¹)	Gross return (₹ ha ⁻¹)	Net return (₹ ha ⁻¹)	Benefit-Cost ratio
T ₁	44,378	113,825	69,447	1.56
T ₂	44,381	120,101	75,720	1.71
T ₃	44,337	132,241	87,904	1.98
T ₄	43,214	93,495	50,281	1.16
T ₅	44,754	97,449	52,695	1.18
T ₆	44,913	98,810	53,897	1.20
T ₇	45,775	117,358	71,583	1.56
T ₈	45,330	90,942	45,612	1.01
T ₉	42,250	62,238	19,988	0.47
T ₁₀	65,350	142,906	77,556	1.19

Table 5 : Pearson's correlation coefficients among weed biomass, nutrient uptake by weeds, post-harvest soil nutrients, grain yield and economic parameters.

Parameters	Weed dry weight	Weed N uptake	Weed P uptake	Weed K uptake	Grain yield	Available N	Available P ₂ O ₅	Available K ₂ O	Net return	Benefit-cost ratio
Weed dry weight	1									
Weed N uptake	0.999	1								
Weed P uptake	0.997	1.000	1							
Weed K uptake	0.999	1.000	0.999	1						
Grain yield	-0.897	-0.882	-0.873	-0.884	1					
Available N	-0.898	-0.896	-0.895	-0.891	0.947	1				
Available P ₂ O ₅	-0.937	-0.932	-0.928	-0.930	0.964	0.984	1			
Available K ₂ O	-0.953	-0.943	-0.937	-0.945	0.973	0.922	0.948	1		
Net return	-0.883	-0.875	-0.870	-0.875	0.961	0.957	0.981	0.917	1	
Benefit-cost ratio	-0.742	-0.744	-0.745	-0.741	0.776	0.837	0.868	0.714	0.920	1

107.00 kg ha⁻¹, respectively). The higher residual nutrient status under T₃ was associated with effective weed suppression, which reduced weed dry weight (34.33 g m⁻²) and nutrient uptake by weeds (4.07 kg N, 1.49 kg P and 4.62 kg K ha⁻¹), thereby conserving a greater proportion of available nutrients in the soil. Conversely, unchecked weed growth in the weedy check resulted in greater nutrient removal by weeds, leading to lower residual soil nutrient status. Similar findings were reported by Pooja *et al.* (2021), who observed improved post-

harvest nutrient availability under effective weed management due to reduced nutrient depletion by weeds. Likewise, Sarma *et al.* (2024) reported that efficient weed management strategies in wet direct-seeded rice improved post-harvest soil fertility by conserving available nutrients. The present findings demonstrate that sequential application of Pretilachlor + Pyrazosulfuron followed by Florpyrauxifen-benzyl + Cyhalofop-butyl effectively conserved soil nutrients without adversely affecting soil physical and biological properties at the recommended application rates.

Economics

Weed management practices significantly influenced the economics of wet direct-seeded rice (Table 4). The cost of cultivation ranged from ₹ 42,250 ha⁻¹ under the

weedy check to ₹ 65,350 ha⁻¹ under the weed-free treatment. Although, the weed-free treatment produced the highest gross return (₹ 142,906 ha⁻¹) owing to its superior grain yield, the higher labour input for maintaining weed-free conditions increased the cost of cultivation, resulting in a comparatively lower benefit-cost ratio (1.19).

T₃ recorded the highest gross return (₹ 132,241 ha⁻¹), net return (₹ 87,904 ha⁻¹) and benefit-cost ratio (1.98). The superior economic performance of T₃ was attributed

to effective season-long weed suppression, which minimized crop-weed competition and nutrient depletion by weeds, resulting in higher grain yield without substantially increasing the cost of cultivation. Similar economic advantages of sequential and integrated weed management practices in direct-seeded rice have been reported by Dhakal *et al.* (2019) and Singh *et al.* (2019). Likewise, Dey *et al.* (2024) emphasized that economically viable weed management practices are essential for improving the profitability and adoption of direct-seeded rice cultivation. In contrast, the weedy check recorded the lowest net return (₹ 19,988 ha⁻¹) and benefit-cost ratio (0.47), reflecting the severe economic losses associated with uncontrolled weed infestation. The findings indicate that sequential herbicide application not only ensured effective weed control but also provided a profitable and economically sustainable weed management strategy for wet direct-seeded rice.

Relationship among weed biomass, post-harvest soil fertility and economic returns

Pearson's correlation analysis revealed strong relationships among weed biomass, nutrient uptake by weeds, post-harvest soil nutrient status, grain yield and economic returns (Table 5). Weed dry weight exhibited strong positive correlations with nitrogen ($r = 0.999$), phosphorus ($r = 0.997$) and potassium uptake ($r = 0.999$) by weeds, indicating that greater weed biomass resulted in increased nutrient removal from the soil. Conversely, weed dry weight was negatively correlated with available nitrogen ($r = -0.898$), available phosphorus ($r = -0.937$) and available potassium ($r = -0.953$), suggesting that effective weed suppression was associated with improved nutrient conservation and improved residual soil fertility.

Grain yield showed strong positive correlations with available nitrogen ($r = 0.947$), available phosphorus ($r = 0.964$), available potassium ($r = 0.973$) and net return ($r = 0.961$), while weed dry weight was negatively correlated with net return ($r = -0.883$) and benefit-cost ratio ($r = -0.742$). These relationships indicate that reducing weed biomass not only minimized nutrient depletion by weeds but also improved crop productivity and economic returns. The correlation analysis therefore confirms that efficient sequential weed management contributes to sustainable rice production by conserving soil nutrients and enhancing farm profitability.

Conclusion

Sequential application of Pretilachlor 30% + Pyrazosulfuron ethyl 0.75% WG @ 615 g ha⁻¹ as PE followed by Florpyrauxifen-benzyl 2.13% + Cyhalofop-butyl 10.64% EC @ 150 g ha⁻¹ as PoE effectively reduced

weed biomass and nutrient removal by weeds, conserved post-harvest soil nutrients and achieved the highest economic returns without adversely affecting soil physical and biological properties. This sequential herbicide programme can be recommended as an efficient and economically sustainable weed management strategy for wet direct-seeded rice under the agro-climatic conditions of Assam.

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Authors' contributions

RD: Conceptualization, investigation, data analysis and manuscript preparation. MJK: Supervision and manuscript review. AB: Methodology and manuscript review. RKS: Investigation and data collection. PB: Investigation and data validation. HS: Methodology and validation. KP: Resources and supervision. NTR: Supervision and manuscript review. KB: Conceptualization, project supervision and manuscript editing. All authors read and approved the final manuscript.

Conflict of interest : Authors do not have any conflict of interests to declare.

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