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Interactive effects of irrigation scheduling and herbicide application on weed dynamics and productivity of dry direct seeded rice (*Oryza sativa* L.)

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Abstract

Dry direct seeded rice (dry-DSR) is a resource efficient alternative to transplanted rice but weed competition and poor water regimes during establishment limit its yield. The interaction between the timing of the first irrigation following pre-emergence herbicide application and subsequent post-emergence weed control remains insufficiently understood. This two-year split-plot study (rabi 2024–25 and 2025–26, 3 replications) at Odisha University of Agriculture and Technology, Bhubaneswar, evaluated irrigation scheduling and post-emergence weed management effects on weed dynamics, yield attributes and productivity. All plots, including the weedy check (W_4), received pre-emergence herbicide at sowing. Irrigation on the day of sowing (I_1) and at 1 day after sowing (I_2) were the most effective. I_2 recorded the lowest pooled weed biomass (31.26 g m^{-2} at 40 days after sowing (DAS); 122.21 g m^{-2} at harvest), statistically at par with I_1. It also gave the highest weed control efficiencies (64.29 % and 57.42 %) and the lowest weed index (27.25 %). Suppressed weeds improved effective tiller density (210.4 m^{-2}), panicle length (17.8 cm) and grains per panicle (87.8), producing the highest grain yield (4116 kg ha^{-1}) and straw yield (6122 kg ha^{-1}). Among weed control practices, the weed-free treatment (W_5) gave 100 % control and the highest panicle length (19.5 cm), grains per panicle (102.4), grain yield (5290 kg ha^{-1}), straw yield (7262 kg ha^{-1}) and harvest index (42.11 %). Among herbicides, the ready-mix of florpyrauxifen-benzyl 2.13 % + cyhalofop-butyl 10.64 % EC at 150 g ha^{-1} (W_3) was best, giving superior weed reduction, crop recovery and productivity. Advancing the first irrigation to the day of sowing or 1 DAS, followed by this post-emergence ready-mix, is a robust strategy for dry-DSR in India's eastern coastal plains. Total irrigation water, water productivity and economic returns were not evaluated.

Keywords: crop yield; dry direct seeded rice; herbicide; irrigation scheduling; weed control efficiency; weed dynamics

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Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population; however, conventional cultivation methods characterised by puddled, transplanted and continuously flooded systems require disproportionately high volumes of irrigation water compared to other cereal crops (1). In response to escalating agricultural constraints, including severe water scarcity, groundwater depletion in primary cultivation zones and surging labor costs, there has been a marked paradigm shift toward direct seeded rice (DSR) (1, 2). Among the various DSR methodologies, dry-direct seeded rice (dry-DSR) has garnered significant traction. By broadcasting pre-germinated or dry seeds directly into unpuddled, aerobic soil, this system substantially mitigates water and labour demands while facilitating earlier crop maturation and enhanced compatibility with mechanised farming (3). Empirical field data further corroborate that dry-DSR can drastically curtail irrigation requirements relative to conventional puddled systems, presenting a viable adaptation strategy for regions facing declining hydrological resources (4). Despite its agronomic advantages, DSR is inherently constrained by the simultaneous germination of rice and weed seeds. This concurrent emergence fosters intense interspecific competition, which can precipitate yield reductions of up to 90 %

(2, 5). Although chemical control remains the most economically viable and pragmatic mitigation strategy, its efficacy is largely contingent upon the integration of pre-emergence (PRE) and post-emergence (POE) herbicides (2, 6). Consequently, the sequential application of PRE and POE herbicides has emerged as a robust paradigm for broad-spectrum weed management, demonstrating a capacity to enhance weed control efficiency (WCE), promote crop vigour and optimise grain yields (7). Recent studies indicate that such sequential protocols can yield weed control efficiencies ranging from 90–96 %, alongside significant improvements in grain production (8). Conversely, reliance on a singular PRE or POE herbicide application frequently proves insufficient. This inadequacy is attributed to dynamic shifts in weed flora composition, differential herbicide tolerance among rice cultivars and the increasing proliferation of herbicide-resistant weed biotypes within intensively managed dry-DSR systems (3). The sustainable intensification of DSR frameworks is fundamentally dependent on the synergistic interplay between early irrigation scheduling and sequential chemical weed control. Unlike the anaerobic conditions of puddled systems, the aerobic soil environment characteristic of DSR actively promotes the rapid proliferation of highly competitive terrestrial weeds. This ecological shift necessitates the maintenance of a strict weed-free interval between 15 and 45 days after sowing (DAS) to avert severe yield penalties (9). Furthermore, herbicidal efficacy is intrinsically linked to irrigation scheduling, as soil moisture dynamics govern the activation, mobility, persistence and root uptake of the chemical agents. Suboptimal irrigation following herbicide application can significantly compromise WCE, either through inadequate chemical activation in dry conditions or excessive leaching under saturated conditions. Therefore, synchronising optimal irrigation protocols with sequential herbicide applications is paramount for maximising weed suppression and sustaining overarching DSR productivity (10, 11). This dynamic underscores the importance of integrating irrigation scheduling with effective weed management practices as complementary components of a holistic weed management strategy for dry-DSR (12).

Consequently, a critical research gap exists regarding the systematic integration of defined irrigation regimes with optimal herbicide sequences to formulate management practices that minimise weed interference, secure grain yields and optimise water-use efficiency (3). Considering these imperatives, the present study was conducted to empirically evaluate the interactive effects of irrigation scheduling and sequential herbicide regimens on the yield attributes and overall productivity of DSR, aiming to delineate an efficacious management strategy that enhances crop performance within irrigated agroecosystems.

Materials and Methods

A field experiment spanning two consecutive rabi seasons (2024–25 and 2025–26) was carried out at the All India Coordinated Research Project on Weed Management Block within the Agronomy Main Research Farm of the Odisha University of Agriculture and Technology (OUAT), Bhubaneswar (20°15′ N, 85°57′ E; 25.9 m above mean sea level). The site lies within the East and South-Eastern Coastal Plain Agro-climatic Zone of Odisha. Prior to sowing, the surface soil layer (0–15 cm) was characterised and found to be sandy loam in texture with medium inherent fertility. The soil was slightly acidic (pH 6.3), non-saline (electrical conductivity (EC) 0.14 dS m^{-1}) and low in organic carbon (0.35 %), with available nitrogen (N), phosphorus (P) and potassium (K) contents of 309.3, 13.11 and 160 kg ha^{-1}, respectively. Soil texture was determined by the International pipette method (13), soil pH by a glass electrode pH meter in a 1 : 2.5 soil : water suspension and electrical conductivity by a conductivity meter in the same suspension (14), organic carbon by the Walkley and Black wet oxidation method (15), available N by the alkaline permanganate method (16), available P by Olsen extraction method (17) and available K by neutral normal ammonium acetate extraction followed by flame photometry (14). The trial was established in a split-plot design replicated thrice. A uniform PRE application of pretilachlor 30 % + pyrazosulfuron-ethyl 0.75 % WG 615 g ha^{-1} was applied to all plots at sowing. Four post-sowing irrigation regimes constituted the main-plot treatments: irrigation applied on the day of sowing (I_1, 0 DAS), at 1 day after sowing (I_2), at 3 DAS (I_3) and at 5 DAS (I_4). The sub-plot treatments comprised five POE weed control strategies: fenoxaprop-ethyl 67 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} (W_1); a ready-mix of bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl 43 g ha^{-1} (W_2); a ready-mix of florpyrauxifen-benzyl 2.13 % w/w + cyhalofop-butyl 10.64 % w/w EC at 150 g ha^{-1} (W_3); a weedy check (W_4) that received no POE weed control (the PRE herbicide only); and a season-long, manually (hand weeding at 15, 30 and 45 DAS) maintained weed-free treatment (W_5). The POE weed management treatments were imposed at 25 DAS and comprised the five treatments (W_1–W_5) described above. Every plot, including the weedy check (W_4), had received the PRE herbicide at sowing. Hence, W_4 is not an absolute untreated control but a treatment without POE weed control (a PRE-only check) All weed WCE, weed index (WI) and yield-loss values reported here are therefore relative to this PRE-treated check and to W_5 and may underestimate the weed pressure and yield loss that would occur in a completely untreated control. Dry direct-seeded rice cultivar “Kalinga Dhan 1201” was sown on 2 December during both experimental seasons at a spacing of 20 × 10 cm. The seed rate was 20 kg ha^{-1}. The sub-plot size was 3 × 4 m (12 m^2) for quadrat observations within plot, with a total harvested area field size of 720 m^2 area. The land was prepared by ploughing 15 days before sowing, followed by final land preparation to obtain a fine and level seedbed. Bunds and drainage channels were

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prepared 7 days before sowing. The first irrigation was applied on a fixed schedule basis as per the main-plot treatments, administered immediately at 0, 1, 3 and 5 DAS. Where such data were not measured, this is acknowledged as a limitation of the study. Subsequent irrigations were scheduled according to crop water requirements rather than a rigid calendar. Soil moisture levels and crop developmental stages were monitored to dictate timing and volume. A fertiliser dose of 80 kg N, 60 kg phosphorus pentoxide (P_2O_5), 40 kg potassium oxide (K_2O) and 5 kg zinc (Zn) ha^{-1} in the form of urea, single superphosphate (SSP), muriate of potash (MOP) and zinc sulfate ($ZnSO_4$) was applied to each treatment. Half of the N and the entire dose of P_2O_5, K_2O and Zn were applied as basal and the remaining half of the N was top-dressed in two equal splits, i.e., 20 kg N ha^{-1} at the active tillering stage (30 DAS) and 20 kg N ha^{-1} at the panicle initiation stage (60 DAS). Weed density and dry matter were assessed using a 50 × 50 cm quadrat placed randomly at 4 locations within each net plot. The recorded data were expressed on a unit-area basis as number of weeds m^{-2} and dry matter (g m^{-2}), respectively and were subjected to square-root transformation, $\sqrt{(x + 1)}$, prior to statistical analysis. The transformed values were used for statistical analysis, while the original values are presented in parentheses where appropriate. These data were used to derive WCE (%), based on the extent of biomass reduction and the WI (%), based on the grain yield loss relative to the weed-free. The equations used were:

$$WCE\ (\%) = [(WDW_C - WDW_T)/WDW_C] \times 100$$

where WDW_C is the weed dry matter (g m^{-2}) in the weedy check (W_4) and WDW_T is the weed dry matter in the treatment plot (W_1, W_2, W_3 or W_5), calculated at 40 DAS and at harvest within each irrigation schedule.

$$WI\ (\%) = [(Y_{WF} - Y_T)/Y_{WF}] \times 100$$

where Y_{WF} is the grain yield (kg ha^{-1}) of the W_5 and Y_T is the grain yield (kg ha^{-1}) of the treatment under consideration, within the same irrigation schedule.

Irrigation and weed management means for WCE and WI were then averaged over the corresponding treatments. At physiological maturity, yield contributing characters were recorded from representative hill samples, while grain and straw yields were determined from net-plot harvests, with grain yield adjusted to 14 % moisture content and expressed in kg ha^{-1}. The values in parentheses for the treatment means (irrigation, weed management and their interaction means) are back-transformed from the means of the transformed data and are therefore not the arithmetic averages of the original values in the cells. The sub-plot area was 12 m² (3 × 4 m) and the total field harvest area was 720 m² per season. This manuscript reports the weed flora, weed density, weed dry matter, WCE, WI, yield attributes, yield and the weed dry weight –grain yield regression of this field experiment. The same field experiment was used to investigate different aspects of the study; however, the data presented in the present manuscript have not been published or reported in any other paper or manuscript. No other publication reports the same dataset or observations from this experiment. All data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design and treatment means were compared using the critical difference (CD) test at the 5 % probability level. Two-year experimental data were analysed and presented as pooled data in tables following the procedure outlined by Gomez and Gomez (18). The linear model for the split-plot design (replications as blocks) was Yijk = μ + ρi + αj + eaij + βk + (αβ)jk + ebijk, where ρi is the replication effect, αj the main-plot irrigation effect, eaij the main-plot error (replication × irrigation), βk the sub-plot weed management effect, (αβ) jk the irrigation × weed management interaction and ebijk the sub-plot error. Irrigation was tested against the main-plot error (error a), whereas weed management and the irrigation × weed management interaction were tested against the sub-plot error (error b); the CD values for comparing weed management means at the same irrigation level (W within I) and irrigation means at the same or different weed management level (I within W) were computed accordingly.

Results

Major weed flora in dry direct seeded rice

The experimental field was naturally infested with mixed weed flora comprising grasses, sedges and broad-leaved weeds (BLWs) (Table 1). Grasses constituted the predominant weed group, with *Echinochloa crus-galli* (L.) P.Beauv., *Echinochloa colona* (L.) Link, *Leptochloa chinensis* (L.) Nees, *Dactyloctenium aegyptium* (L.) Willd. and *Paspalum distichum* L. being the major grassy weed species. The sedge flora was represented by *Cyperus rotundus* L. and *Cyperus difformis* L. The predominant BLWs included *Oldenlandia corymbose* L., *Commelina benghalensis* L., *Eclipta alba* (L.) Hassk., *Ludwigia prostrata* Roxb., *Ammannia baccifera* L., *Portulaca oleracea* L. and *Sphenoclea zeylanica* Gaertn. The predominance of grassy weeds over BLWs and sedges indicated that effective grass weed management is critical for improving the productivity of dry-DSR.

Weed density at different growth stages

Grassy weed density at different growth stages

Irrigation scheduling exerted a significant influence on grassy weed density in the pooled analysis (Table 2). The I_2 regime recorded the lowest weed density, with values of 5.42 (28.38 weeds m^{-2}) and 5.81 (32.76 weeds m^{-2}) at 40 DAS and harvest, respectively. In comparison, I_4 recorded the highest grassy weed density, with values of 6.62 (42.82 weeds m^{-2}) and 6.80 (45.24 weeds m^{-2}) at 40 DAS and at harvest, respectively. Irrigation I_2 reduced grassy weed density by 33.72 % at 40 DAS and 27.59 % at harvest compared with I_4.

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Table 1. Major grassy, sedge and broad-leaved weed species recorded in dry direct-seeded rice under the experimental conditions

Sl. No.	Common name	Scientific name	Family
1	Barnyardgrass	*Echinochloa crus-galli* (L.) P.Beauv.	Poaceae
2	Jungle rice	*Echinochloa colona* (L.) Link	Poaceae
3	Chinese sprangletop	*Leptochloa chinensis* (L.) Nees	Poaceae
4	Crowfoot grass	*Dactyloctenium aegyptium* (L.) Willd.	Poaceae
5	Knotgrass	*Paspalum distichum* L.	Poaceae
6	Purple nutsedge	*Cyperus rotundus* L.	Cyperaceae
7	Smallflower umbrella sedge	*Cyperus difformis* L.	Cyperaceae
8	Diamond flower	*Oldenlandia corymbosa* L.	Rubiaceae
9	Benghal day flower	*Commelina benghalensis* L.	Commelinaceae
10	False daisy	*Eclipta alba* (L.) Hassk.	Asteraceae
11	Creeping water primrose	*Ludwigia prostrata* Roxb.	Onagraceae
12	Blistering ammannia	*Ammannia baccifera* L.	Lythraceae
13	Common purslane	*Portulaca oleracea* L.	Portulacaceae
14	Gooseweed	*Sphenoclea zeylanica* Gaertn.	Sphenocleaceae

Table 2. Influence of irrigation scheduling and sequential herbicide application on weed density, weed control efficiency, weed index in dry direct-seeded rice

Treatments	Weed density (No. m^{-2})						Weed dry matter (g m^{-2})		Weed control efficiency (%)		Weed index (%)
	40 DAS			At harvest			40 DAS	At harvest	40 DAS	At harvest	
	Grasses	BLWs	Sedges	Grasses	BLWs	Sedges					
Irrigation											
I_1 (0 DAS)	5.70 (31.49)	3.97 (14.76)	2.52 (5.35)	5.88 (33.57)	4.86 (22.62)	2.71 (6.34)	5.78 (32.41)	11.18 (123.99)	63.63	56.56	28.94
I_2 (1 DAS)	5.42 (28.38)	3.81 (13.52)	2.47 (5.10)	5.81 (32.76)	4.78 (21.85)	2.65 (6.02)	5.68 (31.26)	11.10 (122.21)	64.29	57.42	27.25
I_3 (3 DAS)	6.23 (37.81)	5.29 (26.98)	2.68 (6.18)	6.45 (40.60)	5.26 (26.67)	2.76 (6.62)	6.37 (39.58)	11.82 (138.71)	58.35	52.55	31.70
I_4 (5 DAS)	6.62 (42.82)	5.39 (28.05)	2.99 (7.94)	6.80 (45.24)	5.30 (27.09)	2.94 (7.64)	6.52 (41.51)	12.20 (147.84)	57.12	49.55	32.43
SEm (±)	0.093	0.052	0.029	0.039	0.039	0.023	0.035	0.026	0.510	0.310	0.987
CD ($p \leq 0.05$)	0.29	0.16	0.09	0.12	0.12	0.07	0.11	0.08	1.58	0.96	3.06
Weed management											
W_1 (Fenoxaprop-ethyl 67 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} (Tank-mix))	6.49 (41.12)	4.83 (22.33)	2.88 (7.29)	6.68 (43.62)	5.46 (28.81)	2.91 (7.47)	6.34 (39.20)	12.77 (162.07)	66.47	55.40	38.22

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Treatments	Weed density (No. m^{-2})						Weed dry matter (g m^{-2})		Weed control efficiency (%)		Weed index (%)
	40 DAS			At harvest			40 DAS	At harvest	40 DAS	At harvest	
	Grasses	BLWs	Sedges	Grasses	BLWs	Sedges					
W_2 (Bispyribac-Sodium + chlorimuron-ethyl + metsulfuron-Methyl (RM) 43 g ha^{-1})	6.31 (38.82)	4.69 (21.00)	2.95 (7.70)	6.46 (40.73)	5.41 (28.27)	3.00 (8.00)	6.25 (38.06)	12.59 (157.51)	67.46	56.73	27.94
W_3 (Florpyrauxifen-benzyl 2.13 % w/w + cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1})	6.12 (36.45)	4.33 (17.75)	2.64 (5.97)	6.35 (39.32)	5.27 (26.77)	2.69 (6.24)	5.97 (34.64)	12.40 (152.76)	70.30	57.97	21.84
W_4 (Weedy check)	10.05 (100.00)	8.23 (66.73)	3.86 (13.90)	10.69 (113.28)	8.11 (64.77)	4.22 (16.81)	10.89 (117.59)	19.14 (365.34)	0.00	0.00	62.39
W_5 (Weed free)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	100.00	100.00	0.00
SEm (±)	0.039	0.054	0.057	0.039	0.050	0.054	0.036	0.039	0.389	0.275	1.182
CD ($p \leq 0.05$)	0.11	0.15	0.16	0.11	0.14	0.15	0.10	0.11	1.09	0.77	3.31
Interaction (I × W)	S	S	S	S	S	S	S	S	S	S	S

DAS: days after sowing; BLWs: broad-leaved weeds; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance; WCE: weed control efficiency; WI: weed index; RM: ready-mix; EC: emulsifiable concentrate; I × W: interaction between irrigation and weed management treatments. Data on weed density and dry weight were subjected to square root transformation √(x+1) before statistical analysis. Values outside parentheses are transformed values; values in parentheses are original values. Values in parentheses for the treatment means (irrigation means, weed management means and their interaction means) are back-transformed from the means of the transformed data; they are not the averages of the original values in the cells. W_4 (weedy check) received the pre-emergence herbicide only (no post-emergence weed control); WCE and WI are computed relative to W_4 and W_5, respectively.

Among the weed management treatments, W_3 recorded the lowest grassy weed density among the herbicidal treatments, with values of 6.12 (36.45 weeds m^{-2}) and 6.35 (39.32 weeds m^{-2}) at 40 DAS and harvest, respectively. The W_4 (PRE herbicide only; no POE control) recorded 10.05 (100.00 weeds m^{-2}) and 10.69 (113.28 weeds m^{-2}) at the respective stages. The W_3 treatment reduced grassy weed density by 63.55 % at 40 DAS and 65.29 % at harvest compared with the W_4. The W_5 completely suppressed grassy weed emergence throughout the observation period, with a transformed value of 1.00 (0.00 weeds m^{-2}).

The interaction between irrigation scheduling and weed management significantly affected grassy weed density at 40 DAS, with critical differences (CD, p = 0.05) of 0.27 for weed management within irrigation schedules (W within I) and 0.22 for irrigation scheduling within weed management practices (I within W) (Table 3). The completely W_5 recorded the lowest grassy weed density (1.00; 0.00 weeds m^{-2}) across irrigation schedules. Among the herbicidal treatments, the lowest grassy weed density was recorded with I_2W_3, with a value of 5.35 (27.62 weeds m^{-2}), which remained statistically at par with I_2W_2 (5.42; 28.38 weeds m^{-2}). Within W_3, irrigation at 1 DAS (I_2; 5.35; 27.62 weeds m^{-2}) and immediately after sowing (I_1; 5.47; 28.92 weeds m^{-2}) resulted in statistically comparable grassy weed densities.

Broad-leaved weed density at different growth stages

The pooled analysis revealed that irrigation scheduling and weed management practices significantly influenced BLW density at both observation stages (Table 2). The irrigation schedule I_2 recorded the lowest BLW density, with values of 3.81 (13.52 weeds m^{-2}) and 4.78 (21.85 weeds m^{-2}) at 40 DAS and harvest, respectively, which was statistically at par with I_1. In contrast, I_4 recorded higher BLW density, with values of 5.39 (28.05 weeds m^{-2}) and 5.30 (27.09 weeds m^{-2}) at 40 DAS and at harvest, respectively. Irrigation I_2 reduced

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BLW density by 51.79 % at 40 DAS and 19.35 % at harvest compared with I_4.

Among the weed management practices, W_3 recorded the lowest BLW density among the herbicidal treatments, with values of 4.33 (17.75 weeds m^{-2}) and 5.27 (26.77 weeds m^{-2}) at 40 DAS and harvest, respectively. This was followed by W_2 and W_1. The W_4 recorded 8.23 (66.73 weeds m^{-2}) and 8.11 (64.77 weeds m^{-2}) at 40 DAS and harvest, respectively. Application of W_3 reduced BLW density by 73.40 % at 40 DAS and 58.67 % at harvest compared with W_4. Broad-leaved weed density at 40 DAS was significantly influenced by the interaction between irrigation scheduling and weed management (CD, p = 0.05: 0.32 for W within I and 0.30 for I within W; SEm = 0.114 and 0.097, respectively) (Table 3). The W_5 recorded no BLW, with a transformed value of 1.00 (0.00 weeds m^{-2}). Among herbicidal treatments, I_2W_3 recorded the lowest BLW density, with a value of 3.02 (8.12 weeds m^{-2}), which was significantly lower than I_2W_2 (3.38; 10.42 weeds m^{-2}) and I_2W_1 (3.67; 12.47 weeds m^{-2}). Under W_3, early irrigation at I_2 (3.02; 8.12 weeds m^{-2}) and I_1 (3.27; 9.69 weeds m^{-2}) maintained significantly lower BLW density than I_3 (5.43; 28.48 weeds m^{-2}) and I_4 (5.61; 30.47 weeds m^{-2}).

Sedge density at different growth stages

Sedge density was significantly influenced by irrigation scheduling and weed management practices at 40 DAS and harvest in the pooled analysis (Table 2). The I_2 recorded the lowest sedge density, with values of 2.47 (5.10 weeds m^{-2}) at 40 DAS, compared with 2.99 (7.94 weeds m^{-2}) under I_4. This represented a 35.77 % reduction in sedge density under I_2. At harvest, I_2 consistently recorded the lowest sedge density (2.65; 6.02 weeds m^{-2}), whereas I_4 recorded the highest (2.94; 7.64 weeds m^{-2}), representing a 21.20 % reduction. Among the weed management practices, W_4 recorded the highest sedge density, with values of 3.86 (13.90 weeds m^{-2}) and 4.22 (16.81 weeds m^{-2}) at 40 DAS and harvest, respectively. Among the herbicidal treatments, W_3 recorded the lowest sedge density, with 2.64 (5.97 weeds m^{-2}) and 2.69 (6.24 weeds m^{-2}) at 40 DAS and harvest, respectively. Compared with W_4, W_3 reduced sedge density by 57.05 % at 40 DAS and 62.88 % at harvest. This was followed by W_1 and W_2.

Sedge weed density at 40 DAS was significantly influenced by the interaction between irrigation scheduling and weed management (CD, p = 0.05: 0.22 for W within I and 0.32 for I within W; SEm = 0.079 and 0.103, respectively). The W_5 recorded the lowest sedge density (1.00; 0.00 weeds m^{-2}). Among herbicidal treatments, I_2W_3 recorded the lowest sedge density (2.38; 4.66 weeds m^{-2}). Within W_3, early irrigation at I_2 (2.38; 4.66 weeds m^{-2}), I_1 (2.48; 5.15 weeds m^{-2}) and I_3 (2.61; 5.81 weeds m^{-2}) resulted in lower sedge density than I_4 (3.07; 8.42 weeds m^{-2}).

Effect on weed dry matter at different growth stages

Based on the pooled analysis, weed dry matter was significantly influenced by both irrigation scheduling and weed management practices at 40 DAS and at harvest (Table 2). The application of I_2 most effectively minimised weed dry matter, recording values of 5.68 (31.26 g m^{-2}) at 40 DAS and 11.10 (122.21 g m^{-2}) at harvest, which was statistically at par with I_1. The I_4 produced the highest dry matter accumulation, with values of 6.52 (41.51 g m^{-2}) at 40 DAS and 12.20 (147.84 g m^{-2}) at harvest. I_2 reduced weed dry matter by 24.69 % at 40 DAS and 17.34 % at harvest compared with I_4. Among the weed management strategies, the RM formulation W_3 emerged as the most effective herbicidal intervention. The W_3 treatment successfully restricted weed dry matter to 5.97 (34.64 g m^{-2}) at 40 DAS and 12.40 (152.76 g m^{-2}) at harvest. The W_4 produced the highest weed dry matter, with values of 10.89 (117.59 g m^{-2}) at 40 DAS and 19.14 (365.34 g m^{-2}) at harvest. Application of W_3 reduced weed dry matter by 70.54 % at 40 DAS and 58.19 % at harvest compared with the W_4. Total weed dry matter at 40 DAS was significantly influenced by the interaction between irrigation scheduling and weed management (CD, p = 0.05: 0.23 for W within I and 0.21 for I within W; SEm = 0.082 and 0.068, respectively) (Table 4). The W_5 recorded the lowest weed dry matter (1.00; 0.00 g m^{-2}). Among herbicidal treatments, I_2W_3 recorded the lowest weed dry matter (5.22; 26.25 g m^{-2}), significantly lower than I_2W_2 (5.62; 30.58 g m^{-2}) and I_2W_1 (5.82; 32.87 g m^{-2}). Within W_3, I_2 (5.22; 26.25 g m^{-2}) recorded significantly lower weed dry matter than I_1 (5.44; 28.59 g m^{-2}), I_3 (6.40; 39.96 g m^{-2}) and I_4 (6.81; 45.38 g m^{-2}).

Table 3. Pooled interaction effect of irrigation schedules and weed management practices on density of grasses and broad-leaved weeds at 40 DAS

Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy check)	W_5 (Weed free)	Mean
A. Density of grassy weeds at 40 DAS (No. m^{-2})						
I_1 (0 DAS)	6.02 (35.24)	5.99 (34.88)	5.47 (28.92)	10.00 (99.00)	1.00 (0.00)	5.70 (31.49)
I_2 (1 DAS)	5.76 (32.18)	5.42 (28.38)	5.35 (27.62)	9.59 (90.97)	1.00 (0.00)	5.42 (28.38)
I_3 (3 DAS)	6.78 (44.97)	6.61 (42.69)	6.51 (41.38)	10.26 (104.27)	1.00 (0.00)	6.23 (37.81)
I_4 (5 DAS)	7.39 (53.61)	7.21 (50.98)	7.16 (50.27)	10.36 (106.33)	1.00 (0.00)	6.62 (42.82)
Mean	6.49 (41.12)	6.31 (38.82)	6.12 (36.45)	10.05 (100.00)	1.00 (0.00)	
				I within W	W within I	

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Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy check)	W_5 (Weed free)	Mean
SEm±				0.071	0.096	
CD (p = 0.05)				0.22	0.27	
B. Density of broad-leaved weeds (BLWs) at 40 DAS (No. m^{-2})						
I_1 (0 DAS)	3.73 (12.91)	3.87 (13.98)	3.27 (9.69)	8.01 (63.16)	1.00 (0.00)	3.97 (14.76)
I_2 (1 DAS)	3.67 (12.47)	3.38 (10.42)	3.02 (8.12)	7.97 (62.52)	1.00 (0.00)	3.81 (13.52)
I_3 (3 DAS)	5.84 (33.11)	5.55 (29.80)	5.43 (28.48)	8.63 (73.48)	1.00 (0.00)	5.29 (26.98)
I_4 (5 DAS)	6.07 (35.84)	5.96 (34.52)	5.61 (30.47)	8.31 (68.06)	1.00 (0.00)	5.39 (28.05)
Mean	4.83 (22.33)	4.69 (21.00)	4.33 (17.75)	8.23 (66.73)	1.00 (0.00)	-
				I within W	W within I	
SEm±				0.097	0.114	
CD (p = 0.05)				0.30	0.32	

DAS: days after sowing; BLWs: broad-leaved weeds; FE: fenoxaprop-ethyl; ES: ethoxysulfuron; BS: bispyribac-sodium; CE: chlorimuron-ethyl; MSM: metsulfuron-methyl; FPB: florpyrauxifen-benzyl; CB: cyhalofop-butyl; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance. Data on weed density and dry weight were subjected to square root transformation √(x+1) before statistical analysis. Values outside parentheses are transformed values; values in parentheses are original values. Values in parentheses for the treatment means (irrigation means, weed management means and their interaction means) are back-transformed from the means of the transformed data; they are not the averages of the original values in the cells. W_1 = Fenoxaprop-ethyl 67 g ha^{-1} + Ethoxysulfuron 18 g ha^{-1} (Tank-mix); W_2 = Bispyribac-Sodium + Chlorimuron-ethyl + Metsulfuron-Methyl (RM) 43 g ha^{-1}; W_3 = Florpyrauxifen-benzyl 2.13 % w/w + Cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1}; W_4 = Weedy check (PRE only, no POE control); W_5 = Weed free.

Table 4. Pooled interaction effect of irrigation schedules and weed management practices on density of sedges and weed dry weight at 40 days after sowing (DAS)

Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy Check)	W_5 (Weed free)	Mean
C. Density of sedges at 40 DAS (No. m^{-2})						
I_1 (0 DAS)	2.70 (6.29)	2.76 (6.62)	2.48 (5.15)	3.65 (12.32)	1.00 (0.00)	2.52 (5.35)
I_2 (1 DAS)	2.61 (5.81)	2.72 (6.40)	2.38 (4.66)	3.65 (12.32)	1.00 (0.00)	2.47 (5.10)
I_3 (3 DAS)	2.97 (7.82)	2.84 (7.07)	2.61 (5.81)	3.99 (14.92)	1.00 (0.00)	2.68 (6.18)
I_4 (5 DAS)	3.24 (9.50)	3.49 (11.18)	3.07 (8.42)	4.15 (16.22)	1.00 (0.00)	2.99 (7.94)
Mean	2.88 (7.29)	2.95 (7.70)	2.64 (5.97)	3.86 (13.90)	1.00 (0.00)	-
				I within W	W within I	
SEm±				0.103	0.079	
CD (p = 0.05)				0.32	0.22	
D. Weed dry weight at 40 DAS (g m^{-2})						
I_1 (0 DAS)	5.87 (33.46)	5.80 (32.64)	5.44 (28.59)	10.80 (115.64)	1.00 (0.00)	5.78 (32.41)
I_2 (1 DAS)	5.82 (32.87)	5.62 (30.58)	5.22 (26.25)	10.73 (114.13)	1.00 (0.00)	5.68 (31.26)
I_3 (3 DAS)	6.82 (45.51)	6.67 (43.49)	6.40 (39.96)	10.97 (119.34)	1.00 (0.00)	6.37 (39.58)
I_4 (5 DAS)	6.85 (45.92)	6.91 (46.75)	6.81 (45.38)	11.05 (121.10)	1.00 (0.00)	6.52 (41.51)
Mean	6.34 (39.20)	6.25 (38.06)	5.97 (34.64)	10.89 (117.59)	1.00 (0.00)	-

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Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy Check)	W_5 (Weed free)	Mean
				I within W	W within I	
SEm±				0.068	0.082	
CD (p = 0.05)				0.21	0.23	

DAS: days after sowing; FE: fenoxaprop-ethyl; ES: ethoxysulfuron; BS: bispyribac-sodium; CE: chlorimuron-ethyl; MSM: metsulfuron-methyl; FPB: florpyrauxifen-benzyl; CB: cyhalofop-butyl; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance. Data on weed density and dry weight were subjected to square root transformation √(x+1) before statistical analysis. Values outside parentheses are transformed values; values in parentheses are original values. Values in parentheses for the treatment means (irrigation means, weed management means and their interaction means) are back-transformed from the means of the transformed data; they are not the averages of the original values in the cells. W_1 = Fenoxaprop-ethyl 67 g ha^{-1} + Ethoxysulfuron 18 g ha^{-1} (Tank-mix); W_2 = Bispyribac-Sodium + Chlorimuron-ethyl + Metsulfuron-Methyl (RM) 43 g ha^{-1}; W_3 = Florpyrauxifen-benzyl 2.13 % w/w + Cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1}; W_4 = Weedy check (PRE only, no POE control); W_5 = Weed free (PRE only, no POE control, hand weeding at 15, 30, 45 DAS).

Effect on Weed control efficiency at different growth stages and weed index

Based on the pooled analysis, both weed control efficiency (WCE %) and the weed index (WI %) were significantly influenced by irrigation scheduling and weed management practices. The irrigation-level WCE and WI values (Table 2) are means over all five weed management treatments, including the weedy check (0 % control by definition) and the W_5 (100 % control and a WI of 0) and therefore describe the irrigation effect across the whole treatment set rather than over the herbicide treatments alone. Because W_4 received the PRE herbicide, WCE (and the WI of the W_4) is expressed relative to a PRE-treated check and not to an untreated control. The application of I_2 consistently optimised herbicidal efficacy, which was at par with I_1. At 40 DAS, the I_2 schedule recorded the highest WCE of 64.29 %, reflecting a 12.6 % improvement over the delayed irrigation I_4, which yielded a WCE of 57.12 %. This suppressive advantage was maintained until harvest, where the I_2 treatment registered a WCE of 57.42 %, constituting a 15.9 % enhancement relative to I_4. Among the herbicidal interventions, the W_3 recorded the highest WCE among the herbicidal treatments. This treatment achieved the highest WCE among the herbicidal selections, recording 70.30 % at 40 DAS and 57.97 % at harvest. These values surpassed the efficacy of the W_2 by 4.2 % and 2.2 % at 40 DAS and at harvest, respectively. As expected, the W_5 maintained absolute 100 % WCE throughout the duration of the study. The WI, which serves as an indicator of yield reduction due to weed competition, closely mirrored the trends observed in WCE. Evaluating the irrigation schedules, the early I_2 regime successfully minimised the WI to 27.25 %, representing a 16.0 % reduction compared to the higher index observed under the delayed I_4 schedule (32.43 %). Within the weed management approaches, the W_3 herbicidal treatment proved highly effective at minimising competitive yield losses, registering the lowest weed index of 21.84 %. This performance equated to a substantial 65.0 % reduction in the WI relative to the W_4, which suffered a severe WI of 62.39 %. Moreover, the W_3 treatment outperformed the W_2 herbicide mixture, lowering the WI by an additional 21.8 %. The W_5 maintained a zero WI, indicative of peak crop yield potential without weed interference.

Effect on yield attributing characters

The irrigation and weed management interaction was significant for effective tillers m^{-2}, panicle length and grains $panicle^{-1}$ but not for 1000-grain weight (Table 5). Among the irrigation schedules, irrigation at 1 DAS (I_2) recorded the highest number of effective tillers (210.4 m^{-2}), panicle length (17.8 cm), grains $panicle^{-1}$ (87.8), which was at par with I_1. In contrast, I_4 resulted in the lowest values for all the attributes, with 156.2 effective tillers m^{-2}, 14.4 cm panicle length, 79.2 grains $panicle^{-1}$. Compared with I_4, I_2 increased the number of effective tillers, panicle length, grains $panicle^{-1}$ by 34.70, 23.61, 10.86 %, respectively.

Weed management practices also significantly affected the development of yield attributing characters. The W_5 recorded the highest number of effective tillers (238.6 m^{-2}), panicle length (19.5 cm), grains per panicle (102.4). Relative to the W_4, W_5 increased these attributes by 97.03, 91.18, 73.27 %, respectively. Among the herbicidal treatments, W_3 recorded the highest values, with 202.6 effective tillers m^{-2}, 18.4 cm panicle length, 91.8 grains $panicle^{-1}$. Compared with the W_4, W_3 increased the number of effective tillers, panicle length and grains $panicle^{-1}$ by 67.30, 80.39, 55.33 %, respectively. The performance of W_3 was also superior to the other herbicidal treatments. Compared with W_2, W_3 recorded 7.25 % more effective tillers, 12.20 % greater panicle length and 9.16 % more grains $panicle^{-1}$. Similarly, W_3 recorded 16.77 % more effective tillers, 16.46 % greater panicle length and 13.47 % more grains per panicle than W_1. The W_4 recorded the lowest values for all the yield attributes. The significant irrigation × weed management interaction for effective tillers per square meter, panicle length and number of grains per panicle indicated that the effect of weed management practices varied with irrigation timing. The irrigation × weed management interaction significantly influenced the number of effective tillers per square meter (CD, p = 0.05: 12.16 for W within I and 14.58 for I within W; SEm = 4.305 and 4.978, respectively). The W_5 recorded the highest number of effective tillers under I_2

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(242.5 m^{-2}), which was at par with I_1 (241.2 m^{-2}), I_3 (237.2 m^{-2}) and I_4 (233.5 m^{-2}). Among herbicidal treatments, I_2W_3 recorded the highest number of effective tillers (238.5 m^{-2}), which was at par with I_1W_3 (227.5 m^{-2}) and I_2W_2 (227.2 m^{-2}). Within W_3, I_2 produced significantly more effective tillers than I_3 and I_4. The irrigation × weed management interaction significantly influenced panicle length (CD, p = 0.05: 1.7 cm for W within I and 1.8 cm for I within W; SEm = 0.59 and 0.63 cm, respectively) (Table 6). The W_5 recorded the longest panicle under I_1 (22.0 cm). Among herbicidal treatments, I_2W_3 recorded the longest panicle (20.1 cm). Within W_3, I_2 (20.1 cm) and I_1 (20.0 cm) were at par and significantly superior to I_3 (17.8 cm) and I_4 (15.6 cm). The irrigation × weed management interaction significantly influenced the number of grains $panicle^{-1}$ (CD, p = 0.05 : 5.5 for W within I and 5.2 for I within W; SEm = 1.931 and 1.826, respectively). The W_5 recorded the highest number of grains under I_2 (104.5 grains $panicle^{-1}$), which was at par with I_1 (103.2), I_3 (101.8) and I_4 (100.0 grains $panicle^{-1}$). Among herbicidal treatments, I_2W_3 recorded the highest number of grains (96.3 grains $panicle^{-1}$). Within W_3, I_2 (96.3 grains $panicle^{-1}$) and I_1 (95.5 grains $panicle^{-1}$) were at par and significantly superior to I_3 (89.3 grains $panicle^{-1}$) and I_4 (86.2 grains $panicle^{-1}$). The irrigation × weed management interaction did not significantly influence 1000-grain weight.

Effect on grain yield, straw yield and harvest index

The final productivity of rice, expressed through grain yield, straw yield and harvest index, varied significantly with irrigation scheduling, weed management and their combined effects (Table 7). Among the irrigation regimes, I_2 recorded the highest grain yield (4116 kg ha^{-1}), straw yield (6122 kg ha^{-1}) and harvest index (39.22 %), which was statistically at par with I_1. The I_4 recorded the lowest grain yield values of 3225 kg ha^{-1}, straw yield 5224 kg ha^{-1} and harvest index 37.67 %, respectively. Compared with I_4, I_2 increased grain yield, straw yield and harvest index by 27.63, 17.19 and 5.32 %, respectively. The W_5 recorded the highest grain yield (5290 kg ha^{-1}), straw yield (7262 kg ha^{-1}) and harvest index (42.11 %), followed by W_3, which recorded 4136 kg ha^{-1} grain yield, 6136 kg ha^{-1} straw yield and 40.10 % harvest index. The W_4 recorded the lowest values, with 1975 kg ha^{-1} grain yield, 3970 kg ha^{-1} straw yield and 32.97 % harvest index. Relative to W_4, the W_5 increased grain yield, straw yield and harvest index by 167.85, 82.92 and 27.72 %, respectively. Among the herbicidal treatments, W_3 increased grain yield, straw yield and harvest index by 109.42, 54.56 and 21.63 %, respectively, over the W_4. Compared with W_2 and W_1, W_3 increased grain yield, straw yield and harvest index by 8.50, 4.11 and 1.65 % and by 25.98, 16.10 and 5.64 %, respectively. The lowest productivity under W_4 demonstrated the substantial adverse effect of unrestricted weed competition on grain and biomass accumulation. Pooled analysis showed a significant irrigation × weed management interaction for grain yield (CD, p = 0.05: 285 kg ha^{-1} for W within I and 371 kg ha^{-1} for I within W; SEm = 101.79 and 119.68 kg ha^{-1}, respectively) (Table 8). The W_5 recorded the highest yield under I_2 (5593 kg ha^{-1}). Among herbicidal treatments, I_2W_3 recorded the highest yield (4756 kg ha^{-1}), significantly exceeding I_2W_2 (4176 kg ha^{-1}) and I_2W_1 (3920 kg ha^{-1}). Within W_3, I_2 (4756 kg ha^{-1}) produced significantly higher grain yield than I_1 (4335 kg ha^{-1}), I_3 (3913 kg ha^{-1}) and I_4 (3540 kg ha^{-1}). Under W_5, I_1 (5583 kg ha^{-1}) and I_2 (5593 kg ha^{-1}) were at par and superior to I_3 (5116 kg ha^{-1}) and I_4 (4868 kg ha^{-1}). Straw yield was significantly influenced by the irrigation × weed management interaction (CD, p = 0.05: 253 kg ha^{-1} for W within I and 393 kg ha^{-1} for I within W; SEm = 90.4 and 126.8 kg ha^{-1}, respectively). The W_5 recorded the highest straw yield under I_2 (7603 kg ha^{-1}). Among herbicidal treatments, I_2W_3 recorded the highest yield (6713 kg ha^{-1}), significantly exceeding I_2W_2 (6226 kg ha^{-1}) and I_2W_1 (5926 kg ha^{-1}). Within W_3, I_2 (6713 kg ha^{-1}) and I_1 (6390 kg ha^{-1}) were at par and significantly superior to I_3 (5913 kg ha^{-1}) and I_4 (5530 kg ha^{-1}).

Table 5. Influence of irrigation scheduling and sequential herbicide application on yield attributes in dry direct-seeded rice

Treatments	Number of effective tillers m^{-2}	Panicle length (cm)	Number of grains $panicle^{-1}$	1000-grain weight (g)
Irrigation				
I_1 (0 DAS)	200.6	16.8	86.9	23.40
I_2 (1 DAS)	210.4	17.8	87.8	23.60
I_3 (3 DAS)	172.6	15.3	80.7	23.32
I_4 (5 DAS)	156.2	14.4	79.2	23.22
SEm (±)	3.16	0.35	0.48	0.42
CD (p = 0.05)	9.8	1.1	1.5	NS
Weed management				
W_1 (Fenoxaprop-ethyl 67 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} (Tank-mix))	173.5	15.8	80.9	23.18
W_2 (Bispyribac-Sodium +	188.9	16.4	84.1	23.35

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Treatments	Number of effective tillers m^{-2}	Panicle length (cm)	Number of grains $panicle^{-1}$	1000-grain weight (g)
chlorimuron-ethyl + metsulfuron-Methyl (RM) 43 g ha^{-1})				
W_3 (Florpyrauxifen-benzyl 2.13 % w/w + cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1})	202.6	18.4	91.8	23.73
W_4 (Weedy check)	121.1	10.2	59.1	23.23
W_5 (Weed free)	238.6	19.5	102.4	23.45
SEm (±)	2.15	0.29	0.72	0.43
CD (p = 0.05)	6.1	0.8	2.0	NS
Interaction (I × W)	S	S	S	NS

DAS: days after sowing; RM: ready-mix; EC: emulsifiable concentrate; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance; NS: non-significant; S: significant.

Table 6. Pooled interaction effect of irrigation schedules and weed management practices on yield attributing characters of dry-DSR

Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy check)	W_5 (Weed free)	Mean
A. Number of effective tillers m^{-2}						
I_1 (0 DAS)	191.2	212.5	227.5	130.5	241.2	200.6
I_2 (1 DAS)	211.2	227.2	238.5	132.5	242.5	210.4
I_3 (3 DAS)	158.5	171.2	185.2	110.8	237.2	172.6
I_4 (5 DAS)	133.2	144.5	159.2	110.5	233.5	156.2
Mean	173.5	188.9	202.6	121.1	238.6	
				I within W	W within I	
SEm±				4.978	4.305	
CD (p = 0.05)				14.58	12.16	
B. Panicle length (cm)						
I_1 (0 DAS)	15.0	16.4	20.0	10.5	22.0	16.8
I_2 (1 DAS)	18.5	19.6	20.1	10.3	20.3	17.8
I_3 (3 DAS)	15.0	15.0	17.8	10.1	18.4	15.3
I_4 (5 DAS)	14.5	14.5	15.6	9.8	17.5	14.4
Mean	15.8	16.4	18.4	10.2	19.5	
				I within W	W within I	
SEm±				0.63	0.59	
CD (p = 0.05)				1.8	1.7	
C. Number of grains $panicle^{-1}$						
I_1 (0 DAS)	83.7	90.5	95.5	61.8	103.2	86.9
I_2 (1 DAS)	89.8	89.9	96.3	58.7	104.5	87.8
I_3 (3 DAS)	77.2	76.7	89.3	58.4	101.8	80.7
I_4 (5 DAS)	73.0	79.4	86.2	57.3	100.0	79.2

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Irrigation	W_1 (FE + ES)	W_2 (BS + CE + MSM)	W_3 (FPB + CB)	W_4 (Weedy check)	W_5 (Weed free)	Mean
Mean	80.9	84.1	91.8	59.1	102.4	
				I within W	W within I	
SEm±				1.826	1.931	
CD (p = 0.05)				5.2	5.5	
D. 1000-Grain weight (g)						
I_1 (0 DAS)	23.3	23.3	23.5	23.5	23.4	23.40
I_2 (1 DAS)	23.4	23.8	23.8	23.1	23.9	23.60
I_3 (3 DAS)	23.0	23.2	23.9	23.2	23.3	23.32
I_4 (5 DAS)	23.0	23.1	23.7	23.1	23.2	23.22
Mean	23.18	23.35	23.73	23.23	23.45	
				I within W	W within I	
SEm±				0.45	0.48	
CD (p = 0.05)				-	-	

DAS: days after sowing; FE: fenoxaprop-ethyl; ES: ethoxysulfuron; BS: bispyribac-sodium; CE: chlorimuron-ethyl; MSM: metsulfuron-methyl; FPB: florpyrauxifen-benzyl; CB: cyhalofop-butyl; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance. W_1 = Fenoxaprop-ethyl 67 g ha^{-1} + Ethoxysulfuron 18 g ha^{-1} (Tank-mix); W2 = Bispyribac-Sodium + Chlorimuron-ethyl + Metsulfuron-Methyl (RM) 43 g ha^{-1}; W_3 = Florpyrauxifen-benzyl 2.13 % w/w + Cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1}; W_4 = Weedy Check (PRE only, no POE control); W_5 = Weed free.

Table 7. Influence of irrigation scheduling and sequential herbicide application on grain yield, straw yield and harvest index in dry direct-seeded rice

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
Irrigation			
I_1 (0 DAS)	4001	6012	38.93
I_2 (1 DAS)	4116	6122	39.22
I_3 (3 DAS)	3455	5426	38.25
I_4 (5 DAS)	3225	5224	37.67
SEm (±)	40.3	35.8	0.161
CD ($p \leq 0.05$)	125	111	0.5
Weed management			
W_1 (Fenoxaprop-ethyl 67 g ha^{-1} + ethoxysulfuron 18 g ha^{-1} (Tank-mix))	3283	5285	37.96
W_2 (Bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl (RM) 43 g ha^{-1})	3812	5826	39.45
W_3 (Florpyrauxifen-benzyl 2.13 % w/w + cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1})	4136	6136	40.1
W_4 (Weedy check)	1975	3970	32.97
W_5 (Weed-free)	5290	7262	42.11
SEm (±)	66.4	70.4	0.218
CD ($p \leq 0.05$)	186	197	0.61
Interaction (I × W)	S	S	S

DAS: days after sowing; RM: ready-mix; EC: emulsifiable concentrate; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance; S: significant

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Regression analysis of weed dry weight and grain yield

Linear regression analysis (pooled data) showed a strong, significant negative relationship between weed dry weight at 40 DAS and grain yield (Fig. 1). The analytical unit was the treatment-combination mean (pooled over three replications and two seasons), so the 20 points are means of replicated plots that share levels of the same two factors and are not fully independent observations; the regression is therefore descriptive. Original (untransformed) weed dry weight values from all 20 treatment combinations (four irrigation schedules × five weed management practices) were used in the analysis. The fitted model was $y = -27.54x + 4968.47$ ($R^2 = 0.860$, $r = -0.927$, $p < 0.001$, n = 20), where y is grain yield (kg ha^{-1}) and x is weed dry weight at 40 DAS (g m^{-2}). Grain yield therefore declined by about 27.5 kg ha^{-1} (slope SE = 2.62; 95 % CI -33.0 to -22.0) for every 1 g m^{-2} increase in weed dry weight across treatment means, which is an association and not a causal estimate of yield loss per unit of weed biomass and weed dry weight alone accounted for about 86 % of the variation in grain yield in the pooled data. Four weed-free points sat at x = 0 and four weedy-check points at x approximately 114–121 g m^{-2}; because these two groups form tight clusters at the extremes of the weed dry weight range and largely drive the fit, the significance level and the proportion of variance explained should be interpreted with caution. Within the weedy check alone, the relationship was also negative (slope = −42 kg ha^{-1} per g m^{-2}), as yield declined with delayed irrigation (from 2133 kg ha^{-1} at I_2 to 1843 kg ha^{-1} at I_4). Excluding both extreme groups (herbicide treatments only, n = 12), the slope was steeper (-73 kg ha^{-1} per g m^{-2}) (Standard error, SE = 12.2; $p < 0.001$) but the coefficient of determination was lower ($R^2 = 0.78$). The intercept (4968.47 kg ha^{-1}) represents the projected yield under weed-free conditions, which agrees closely with the observed yields of the W_5 (4868–5593 kg ha^{-1}). These results show that weed competition at the critical early growth stage was a major factor reducing grain yield and that treatments giving better weed control at 40 DAS gave correspondingly higher yields.

Table 8. Pooled interaction effect of irrigation schedules and weed management practices on grain yield and straw yield of dry-DSR

Irrigation	W_1 (Fenoxaprop-ethyl 67 g ha^{-1} + Ethoxysulfuron 18 g ha^{-1})	W_2 (Bispyribac-Sodium + Chlorimuron-ethyl + Metsulfuron-Methyl (RM) 43 g ha^{-1})	W_3 (Florpyrauxifen-benzyl 2.13 % w/w + Cyhalofop-butyl 10.64 % w/w EC (RM) 150 g ha^{-1})	W_4 (Weedy check)	W_5 (Weed free)	Mean
A. Grain yield (kg ha^{-1})						
I_1 (0 DAS)	3848	4200	4335	2041	5583	4001
I_2 (1 DAS)	3920	4176	4756	2133	5593	4116
I_3 (3 DAS)	2796	3568	3913	1883	5116	3455
I_4 (5 DAS)	2568	3306	3540	1843	4868	3225
Mean	3283	3812	4136	1975	5290	-
				I within W	W within I	
SEm±				119.68	101.79	
CD (p = 0.05)				371	285	
B. Straw yield (kg ha^{-1})						
I_1 (0 DAS)	5803	6223	6390	c050	7593	6012
I_2 (1 DAS)	5926	6226	6713	4143	7603	6122
I_3 (3 DAS)	4835	5540	5913	3851	6991	5426
I_4 (5 DAS)	4576	5316	5530	3836	6860	5224
Mean	5285	5826	6136	3970	7262	-
				I within W	W within I	
SEm±				126.8	90.4	
CD (p = 0.05)				393	253	

DAS: days after sowing; RM: ready-mix; EC: emulsifiable concentrate; SEm (±): standard error of the mean; CD: critical difference at the 5 % level of significance.

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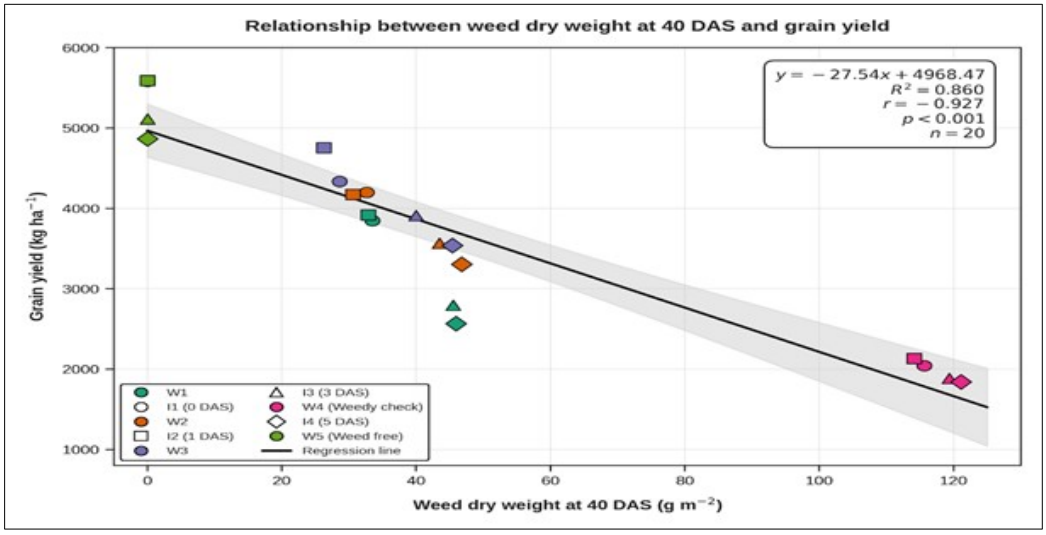


Fig. 1. Relationship between weed dry matter at 40 days after sowing and grain yield of dry direct-seeded rice across irrigation × weed-management treatment combinations (n = 20).

Discussion

Influence of irrigation scheduling and weed management on weed flora in dry direct seeded rice

The experimental field supported a diverse weed community comprising grasses, sedges and BLWs, with grasses forming the predominant group. The major grassy weeds identified were *E.crus-galli*, *E. colona*, *L. chinensis*, *D. aegyptium* and *P. distichum*, while *C. rotundus* and *C. difformis* represented the sedge group. The BLW flora consisted mainly of *O. corymbosa*, *C. benghalensis*, *E. alba*, *L. prostrata*, *A. baccifera*, *P. oleracea* and *S. zeylanica*. The predominance of grasses observed in the present investigation is consistent with earlier reports that Poaceae and Cyperaceae constitute major components of the weed flora in DSR. In addition, *Echinochloa* spp. and *Cyperus* spp. are well adapted to DSR, especially in how they germinate and establish under different post-sowing water regimes (19). The presence of *E. crus-galli*, *E. colona* and *L. chinensis* in this experiment matches reports from DSR fields in several regions of India. These 3 species, together with the sedge *C. rotundus*, are recognised as major weeds of dry-DSR (20). *Echinochloa* spp. and *L. chinensis* have likewise been described as the dominant grasses, accompanied by BLWs such as *E. alba* and *Ludwigia* spp. and by *Cyperus* spp. sedges (21). Other work also found *E. crus-galli*, *E. colona* and *L. chinensis* to be the most prevalent species in irrigated dry-seeded rice, which supports their dominance under dry-DSR conditions (22). The predominance of grassy weeds in the present study may be associated with the dry-seeded establishment system, in which rice and weeds emerge simultaneously and the crop does not possess the initial competitive advantage associated with transplanted rice. The dominance of *Echinochloa* spp. is particularly important because these species are highly competitive grasses in rice ecosystems. *Echinochloa crus-galli* possesses strong ecological adaptability, with its emergence and subsequent growth being markedly influenced by soil moisture and flooding (23). Thus, the composition of weed flora recorded in the present experiment highlights the importance of simultaneously managing grassy weeds, sedges and BLWs rather than relying on a weed-control practice directed against only one weed group. The diverse weed spectrum observed in the present experiment is also characteristic of eastern Indian DSR systems. Irrigation scheduling significantly affected the density of grasses, BLWs and sedges, with I_2 or immediate irrigation on the same day of sowing consistently recording lower weed density than I_4. These results demonstrate that the timing of the first irrigation after sowing substantially influenced subsequent weed establishment in dry-DSR. The lower weed density under I_1 and I_2 can be explained by the interaction between early soil wetting and weed emergence during the initial crop establishment period. In dry-DSR, the post-sowing water regime can determine which weed species emerge and how rapidly they develop. Weed species differ considerably in their response to post-sowing water regimes, making water management an important component of weed management in DSR (19). The lower grassy weed density under I_2 and I_1 may therefore reflect greater suppression of early emerging grasses following timely irrigation. The present results extend this concept under the specific dry-DSR conditions of the experiment, where I_2 and I_1 resulted in lower densities of all three weed groups than the delayed 5-DAS irrigation.

Effect of irrigation on weed dynamics

The current investigation demonstrates that the precise timing of irrigation following PRE herbicide application fundamentally dictates weed emergence and development in dry-DSR. I_2 and I_1 along with PRE herbicide treatment consistently reduced the density and dry biomass of grassy, broad-leaved and sedge weeds compared to delayed irrigation schedules (I_3 and I_4). Treatment I_2 recorded the lowest weed dry matter, 5.68 (31.26 g m^{-2}) at 40 DAS and 11.10 (122.21 g m^{-2})

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at harvest and was at par with I_1. In comparison, I_4 recorded 6.52 (41.51 g m^{-2}) and 12.20 (147.84 g m^{-2}), so I_2 was 24.69 % and 17.34 % lower, respectively. I_2 also gave the highest WCE (64.29 % and 57.42 %) compared with 57.12 % and 49.55 % under I_4 and the lowest weed index (27.25 % vs 32.43 %). This superior weed suppression may plausibly be attributed to the timely activation and uniform distribution of the PRE herbicide within the soil solution, which effectively restricts early weed establishment in the germination zone. On the other hand, I_4 may reduce herbicide bioavailability during the critical emergence period, thereby potentially promoting weed germination, prolonged crop-weed competition for light and nutrients and excessive biomass accumulation during the vegetative growth stages (9, 24). These findings align with prior research establishing that optimal soil moisture immediately following herbicide application is a critical determinant of herbicidal efficacy in dry-DSR (25) and that matching irrigation with herbicide application significantly strengthens both weed suppression and herbicidal persistence (26). The improved weed control observed under early irrigation may be attributed, in part, to enhanced herbicide activation and availability in the soil, facilitating effective suppression of emerging weeds. In addition, irrigation timing may have directly influenced weed emergence and crop establishment, thereby contributing to differences in weed pressure and crop performance. These findings are supported by previous reports demonstrating the influence of soil-saturation timing following PRE herbicide application on the control of major rice weeds (27), as well as the effects of post-sowing water regimes on weed emergence and growth in direct-seeded rice (19).

The response of weeds and yield to the timing of irrigation in the present study can be compared with earlier work in terms of similarities and differences. In agreement with reports that matching irrigation with herbicide application strengthens weed suppression (25, 26), the early irrigation schedules (I_1 and I_2) lowered weed dry matter at 40 DAS to 32.41 and 31.26 g m^{-2}, respectively, against 41.51 g m^{-2} under I_4 and raised grain yield from 3225 kg ha^{-1} (I_4) to 4116 kg ha^{-1} (I_2). In contrast, early soil saturation following PRE herbicide application was reported to increase herbicide injury to rice seedlings, with irrigation recommended to be delayed by at least one week after application; however, in the present study, delayed irrigation (I_3 and I_4) was associated with greater weed pressure and lower grain yield (27).This difference may be related to the herbicides tested (oxadiazon, pendimethalin and pretilachlor with safener in that study, against a pretilachlor + pyrazosulfuron-ethyl ready-mix here), to the soil-saturation treatments imposed in that study, which differ from the field irrigation applied here and to the fact that crop injury is not reported in the present study. In addition to irrigation scheduling studies, the response to the timing of the first irrigation in the present study can be quantitatively compared with previous findings (10). In that study on a clay loam soil in Punjab, yields of dry-seeded rice declined when irrigation was delayed to the 40 and 70 kPa soil water tension thresholds, more so in the drier year and soil tension was recommended to be kept below 20 kPa, whereas in the present study only the timing of the first irrigation after sowing differed and later irrigations were the same for all plots. Delaying the first irrigation from I_2 to I_4 raised weed dry matter at 40 DAS from 31.26 to 41.51 g m^{-2} (32.79 % higher), lowered the WCE at 40 DAS from 64.29 % to 57.12 % and lowered grain yield from 4116 to 3225 kg ha^{-1}, which is a yield gain of 27.63 % (891 kg ha^{-1}) from irrigating at I_2 instead of I_4. The two studies therefore agree in the direction of the yield response to the timing of water application, but they are not directly comparable in magnitude because they manipulated different irrigation variables.

Effect of weed management on weed dynamics

Among the evaluated weed management strategies, the W_3 consistently outperformed W_1 and W_2. W_3 recorded the lowest weed dry matter among the herbicide treatments, 5.97 (34.64 g m^{-2}) at 40 DAS and 12.40 (152.76 g m^{-2}) at harvest. Based on the original values, this was 70.54 % and 58.19 % lower than the W_4, which recorded 10.89 (117.59 g m^{-2}) and 19.14 (365.34 g m^{-2}). W_3 also gave the highest WCE (70.30 % and 57.97 %) and the lowest weed index (21.84 %), compared with 27.94 % for W_2 and 38.22 % for W_1. At 40 DAS, I_2W_3 was the best combination with 5.22 (26.25 g m^{-2}), significantly lower than I_2W_2 with 5.62 (30.58 g m^{-2}) and I_2W_1 with 5.82 (32.87 g m^{-2}). This pronounced efficacy is likely related to its dual, complementary modes of action: florpyrauxifen-benzyl (an Herbicide Resistance Action Committee (HRAC) Group 4 synthetic auxin) delivers robust control over BLWs and sedges, while cyhalofop-butyl (an HRAC Group 1 acetyl-CoA carboxylase (ACCase) inhibitor) efficiently targets annual grasses (28, 29). Together, they systematically suppress the diverse mixed weed flora typical of dry-DSR. Previous studies corroborate that applying this RM 150 g ha^{-1} effectively manages complex weed populations including *E. crus-galli* and *Cyperus iria* L. leading to significantly reduced weed biomass and enhanced crop competitiveness, effective tillers and grain yield compared to conventional POE treatments (5, 28, 30). Compared quantitatively with the study cited above (28), the response to the florpyrauxifen-benzyl + cyhalofop-butyl ready-mix in the present work was similar in direction but different in magnitude. In that kharif trial in Punjab (cultivar PR 126; ready-mix at 150 g a.i. ha^{-1} applied alone at 20 DAS, without a PRE herbicide), grain yield under the ready-mix was 7.54 and 7.19 t ha^{-1} in two years, which was 60.4 % and 82.0 % higher than the unsprayed control and effective tillers were 20.6 % and 15.9 % higher; the weed control efficiency for *E. crus-galli*, calculated from the original weed biomass means in their Table 3 and 4, was about 97 % and 95 % at 45 days after application (28). The WCE naturally declined from 40 DAS to harvest across all treatments, which may be attributed to gradual herbicide dissipation and the emergence of late-season weeds, a pattern commonly observed under sequential herbicide application (26, 30). Consequently, the

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combination of early irrigations (I_1 and I_2) and the W_3 herbicide treatment resulted in the lowest weed index. Because the WI serves as an integrated metric of economic yield loss driven by weed competition, this reduction confirms that efficient, season-long weed management translates directly into maximised resource utilisation and preserved crop productivity (28). Compared with other sequential herbicide programmes, the weed control efficiencies observed here were lower. Sequential PRE and POE programmes have been reported to give WCE of 90–96 % (8) and the florpyrauxifen-benzyl + cyhalofop-butyl ready-mix gave about 95–97 % control of *E. crus-galli* in the previous study (28), whereas W_3 recorded 70.30 % at 40 DAS and 57.97 % at harvest in the present study. The direction of response is therefore similar (the RM was the most effective POE treatment), but the magnitude differs. Part of this difference may arise because WCE here was calculated against W_4 that had also received the PRE herbicide and because it is based on weed biomass of the whole weed flora and not on a single species as in that study; these possible reasons were not tested in the present study. Herbicide sequences in DSR have also been evaluated, with the efficacy of oxadiazon followed by fenoxaprop + ethoxysulfuron and oxadiazon followed by penoxsulam + cyhalofop reported to be lower under zero-tillage than under conventional tillage. Additionally, the grain yield of the one-hand-weeded zero-tillage control was 0.9–1.5 t ha^{-1} lower than that of the conventional-tillage control (11). In the present study, conducted on a conventionally prepared seedbed, the grain yield of the herbicide treatments was lower than that of the W_5 (5290 kg ha^{-1}) by 1154 kg ha^{-1} for W_3 (4136 kg ha^{-1}), 1478 kg ha^{-1} for W_2 (3812 kg ha^{-1}) and 2007 kg ha^{-1} for W_1 (3283 kg ha^{-1}) and the W_4 (1975 kg ha^{-1}) was 3315 kg ha^{-1} lower. The yield gaps under the herbicide treatments are thus of the same order as the penalty reported in previous studies (11), whereas the larger loss in the W_4 is consistent with it having received no POE weed control, in contrast to the hand-weeded control in (11); the tillage systems, herbicides, cultivars and seasons differ, so this comparison is indicative only.

The performance of W_3 was, however, not uniform across weed groups or sampling stages. Relative to the W_4, W_3 reduced the density of BLWs by 73.40 % and 58.67 %, grasses by 63.55 % and 65.29 % and sedges by 57.05 % and 62.88 % at 40 DAS and at harvest, respectively (Table 2). Compared with W_2, the advantage of W_3 at 40 DAS was small for grasses (about 6 %) but larger for BLWs (about 16 %) and sedges (about 23 %) and at harvest it remained marginal for grasses (about 4 %) and BLWs (about 5 %) but for sedges (about 22 %). Grasses nevertheless remained the most abundant group under W_3 (36.45 and 39.32 weeds m^{-2} at 40 DAS and harvest), even though cyhalofop-butyl is a graminicide and the reduction in sedges at 40 DAS was the smallest of the three groups despite the reported activity of florpyrauxifen-benzyl on sedges. This suggests that a single POE application at 25 DAS did not fully suppress late-emerging or less-sensitive grass cohorts. Overall, the activity of W_3 across all three weed groups supports its suitability for the mixed weed flora of dry-DSR, but its advantage over W_2 and W_1 was modest for grasses, the dominant group. Moreover, W_3 plots still carried 152.76 g m^{-2} of weed dry matter at harvest (about 42 % of that in the weedy check) and WCE declined from 70.30 % at 40 DAS to 57.97 % at harvest. This indicates that a single POE application did not provide season-long control and that late-season flushes may require an additional measure. Because W_4 received the PRE herbicide, these reductions represent the benefit of POE management over a PRE-only check; the benefit relative to a completely untreated control and the corresponding yield loss, may be greater.

Ultimately, the significant interaction between irrigation scheduling and weed management highlights that the timing of post-application moisture strictly governs herbicide performance. Dry-DSR is characterised by a staggered weed emergence pattern; therefore, optimal management requires a sequential approach. Early irrigation I_2 and I_1 may create favourable soil moisture_conditions to activate the PRE herbicide pretilachlor + pyrazosulfuron and eliminate the initial weed flora, while the subsequent POE application of florpyrauxifen-benzyl + cyhalofop-butyl suppresses late emerging survivors. This synchronised, sequential strategy minimises crop–weed competition during critical growth stages and is widely recognised as one of the most effective and sustainable approaches for optimising crop productivity in direct seeded rice (2, 9, 27).

Effect of irrigation on yield attribute and yield

The growth, yield attributes and overall productivity of dry-DSR were significantly improved through appropriate application of irrigation scheduling. Irrigation I_2 gave the highest effective tillers (210.4 m^{-2}), panicle length (17.8 cm) and grains $panicle^{-1}$ (87.8) over I_4 (156.2 tillers m^{-2}, 14.4 cm, 79.2 grains). Thousand grain weight was not significantly affected. Irrigation I_2 and I_1 along with PRE herbicide application may have been important for maintaining favourable soil moisture conditions required for effective herbicide activation and uniform distribution within the weed germination zone. This timing may have reduced the risks of excessive herbicidal dilution, soil surface desiccation and delayed herbicide activation that may occur under inappropriate or delayed irrigation schedules (9, 27). By maintaining adequate soil moisture soon after herbicide application, the I_1 and I_2 schedule facilitated effective suppression of early season weed emergence and reduced crop weed competition during the critical crop establishment phase (30). Consequently, the rice crop may have utilised available moisture more effectively, resulting in improved yield attributing characters compared with delayed irrigation schedules (31).

Effect of weed management on yield attribute and yield

Irrespective of irrigation scheduling, weed management practices exerted a pronounced influence on crop

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growth and productivity. Among the herbicidal treatments, the sequential application of W_3 consistently resulted in superior agronomic performance compared with the other POE herbicide treatments. Among weed management treatments, W_5 recorded 238.6 tillers m^{-2}, 19.5 cm panicle length and 102.4 grains $panicle^{-1}$, followed by W_3 (202.6, 18.4 cm and 91.8). W_3 exceeded the weedy check by 67.30 %, 80.39 % and 55.33 %. The effective suppression of diverse weed flora, including grasses, sedges and BLWs, under W_3 reduced crop-weed competition and produced greater production of effective tillers (2, 5, 28). Effective weed reduction reduced crop weed competition for available resources and promoted efficient utilisation and translocation of assimilates towards developing grains. Thus, the superior weed suppression achieved through the W_3 treatment enhanced crop growth, yield attributes and overall productivity of dry-DSR under non-flooded conditions (29). In comparison with the previous study, the ready-mix improved effective tillers and grain yield in the same direction (28), but the gains over the weedy check differed in size: W_3 increased effective tillers by 67.30 % and grain yield by 109.42 % in the present study, against 15.9 to 20.6 % and 60.4 to 82.0 % in that study. The weedy check in the present study suffered a weed index of 62.39 %, which indicates severe weed pressure and may partly explain the larger response, although differences in cultivar, season and location could also contribute and were not tested.

Relationship between weed dry weight and grain yield

The strong negative relationship between weed dry weight at 40 DAS and grain yield (r = -0.927; R^2 = 0.860; p < 0.001) clearly indicated that greater early-season weed biomass was associated with substantial reductions in rice productivity. The 40 DAS stage is particularly important in dry-DSR because the crop and weeds compete intensely for water, nutrients, light and growing space during the early crop-growth period. Earlier studies have identified approximately the first 40 DAS as the critical period of weed competition in DSR, with delayed weed control resulting in appreciable yield losses (32, 33). The regression slope further showed that each 1 g m^{-2} increase in weed dry weight at 40 DAS was associated with a reduction of approximately 27.5 kg ha^{-1} in grain yield, indicating a strong association between early weed biomass and crop productivity. The lower coefficient of determination obtained after excluding the weed-free and weedy-check groups (R^2 = 0.78; slope = −73 kg ha^{-1} per g m^{-2}) further suggests a consistent negative association between weed biomass and yield among the herbicide-treated combinations. The close agreement between the regression intercept (4968 kg ha^{-1}) and the observed yield range of the W_5 further supports the overall trend. Collectively, these findings demonstrate that effective suppression of weed biomass during the early growth period was closely associated with improved grain yield in dry-DSR.

Conclusion

The significant interaction between irrigation scheduling and weed management showed that the performance of herbicides in dry direct seeded rice (dry-DSR) depends on the timing of the first irrigation. Irrigation one day after sowing, or immediately after sowing, along with pre-emergence (PRE) herbicide application reduced weed dry matter at 40 days after sowing (DAS) (31.26 g m^{-2} under I_2 against 41.51 g m^{-2} under I_4) and increased grain yield (4116 kg ha^{-1} against 3225 kg ha^{-1}) compared to delayed irrigation. Among post-emergence (POE) treatments, florpyrauxifen-benzyl 2.13 % + cyhalofop-butyl 10.64 % EC at 150 g ha^{-1} (W_3) provided the most widespread suppression of grassy weeds, BLWs and sedges and the highest yield (4136 kg ha^{-1}) among the herbicide treatments. Early irrigation with PRE herbicide pretilachlor 30 % + pyrazosulfuron-ethyl 0.75 % WG 615 g ha^{-1}, followed by the POE application of florpyrauxifen-benzyl + cyhalofop-butyl at 25 DAS, is therefore recommended as an effective weed management strategy for dry-DSR in the eastern coastal plains of India. Future research should focus on monitoring soil moisture dynamics, herbicide residues and herbicidal activity within the weed seed germination zone to elucidate the underlying mechanisms. Further studies should also validate the effectiveness of this approach across diverse soil types, locations and rice cultivars. In addition, the inclusion of irrigation-timing treatments without PRE herbicide application would help distinguish the effects of irrigation scheduling from herbicide–irrigation interactions, while assessment of water productivity would provide further insights into resource-use efficiency.

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Authors' contributions

DDP and ST conceptualised the research. RD and ST were responsible for experimental planning and methodological design. DDP, ST, AB, ACD, AKS, RB and GP jointly conducted field investigations, data curation and laboratory analyses. DDP, AKS, ACD, SK and AG performed statistical analysis, data visualisation and validation. DDP prepared the original manuscript draft. PM, AKS, ST, NP, SM and SSD provided technical guidance, critical review and manuscript editing. RD and PM were responsible for

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project administration and overall supervision. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, generative AI-assisted tools, specifically ChatGPT and Claude AI (Anthropic), were used only for language improvement, grammar correction and editing of the text. After using these tools, the authors reviewed and edited all AI-assisted content and take full responsibility for the content of the publication.

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