GMR
The Original

INFLUENCE OF IRRIGATION SCHEDULING AND WEED MANAGEMENT PRACTICES ON THE GROWTH OF DRY DIRECT SEEDED RICE (*ORYZA SATIVA L.*)

Dharani Dhar Pradhan[1], Suchismita Tripathy[2*], Rabiratna Dash[3], Prasannajit Mishra[4], Narayana Panda.[5], Rajkumari Bhol[6], Anupama Baliarsingh[7], A.K. Sethy[8], A.C Dash[9], G. Prameela[10], S. Karubakee[11], Soumya Mohanty[12], Arunima Goswami[13], Susree Snigdha Das[14] , Rameswar Jena[15]

[1]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003. Email id: dharanidhar.rs23@ouat.ac.in, Orcid id: https://orcid.org/0009-0008-4316-4212
[2*]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003. Email id: suchismita.agro@ouat.ac.in, Orcid id: https://orcid.org/0009-0009-3611-9699
[3]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003. Email id: rabiratnadashouat@gmail.com, Orcid id: https://orcid.org/0009-0004-5284-8043
[4]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003. Email id: pjmishra@ouat.ac.in, Orcid id: https://orcid.org/0000-0002-7567-7580
[5]Department of Soil Science, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: npandasoils@gmail.com, Orcid id: https://orcid.org/0000-0002-0388-1232
[6]Department of Plant Physiology, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: rajkumaribhol@ouat.ac.in, Orcid id: https://orcid.org/0000-0002-8449-3329
[7]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India.Email id: anupamabs@ouat.ac.in, Orcid id: https://orcid.org/0009-0004-0324-0306
[8]AICRP on Groundnut, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: aksethy@ouat.ac.in, Orcid id: https://orcid.org/0009-0001-1381-1166
[9]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, Email id: India.acdash@ouat.ac.in, Orcid id: https://orcid.org/0009-0002-4398-6351
[10]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: drvgp126@gmail.com, Orcid id: https://orcid.org/0000-0001-8447-6257
[11]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: karubakee.kbk@gmail.com, Orcid id: https://orcid.org/0009-0000-7741-6045
[12]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: soumyamohanty2106@gmail.com, Orcid id: https://orcid.org/0009-0005-7015-4587
[13]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: arunima.rs23@ouat.ac.in , Orcid id: https://orcid.org/0009-0000-2965-6271
[14]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: susreedas1998@gmail.com, Orcid id: https://orcid.org/0009-0003-5525-9853
[15]Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email id: jrameswar@gmail.com, Orcid id: https://orcid.org/0009-0000-8737-0378

ABSTRACT:
The emergence of BCR-ABL kinase domain mutations remains a major challenge in the management of Philadelphia chromosome-positive leukaemia's, including Chronic Myeloid Leukaemia (CML) and Philadelphia chromosome-positive Acute Lymphoblastic Leukaemia (Ph+ ALL), due to the development of resistance against tyrosine kinase inhibitors (TKIs). This study presents an integrated computer-aided drug design (CADD), Machine Learning (ML), and Artificial Intelligence (AI) framework for the identification and prioritization of potential therapeutic inhibitors targeting the BCR-ABL kinase domain using the experimentally resolved crystal structure PDB ID: 8I7Z. The computational workflow included CADD score-based variant prioritisation, structural bioinformatics, molecular docking, AI-based protein language models (ProtBERT and ESM2), and machine learning algorithms to evaluate mutation pathogenicity and inhibitor-binding potential. Structural validation confirmed the reliability of the selected protein model, with a high ERRAT quality score (97.210), while BLAST analysis showed near-complete sequence identity to the human ABL1 kinase domain. Molecular docking of clinically relevant inhibitors, including Nilotinib, Ponatinib, Asciminib, Dasatinib, Bosutinib, and Telaglenastat, identified distinct binding cavities and revealed Nilotinib as the strongest ATP-pocket binder with the highest predicted binding affinity. AI-driven sequence embedding and clustering successfully differentiated structurally conserved homologs, whereas machine learning models facilitated mutation prioritization and prediction of drug-resistance patterns. Furthermore, ADMET and toxicity profiling supported the pharmacological evaluation of candidate inhibitors. The integrated computational pipeline provides a comprehensive framework for prioritizing clinically significant BCR-ABL mutations, understanding structural mechanisms of drug resistance, and accelerating the discovery of next-generation targeted therapeutics. This multidisciplinary strategy demonstrates the potential of combining CADD, structural bioinformatics, machine learning, and artificial intelligence to support precision oncology and guide future experimental validation for personalized treatment of BCR-ABL-positive leukemias.

KEYWORDS: BCR-ABL; Computer-Aided Drug Design (CADD); Machine Learning; Artificial Intelligence; Next-Generation Sequencing; Molecular Docking; Structural Bioinformatics; Biopython; Precision Oncology; Tyrosine Kinase Inhibitors.

1. INTRODUCTION

Rice (Oryza sativa L.) is one of the most important staple food crops, providing nutritional security and livelihoods to a substantial proportion of the global population. However, conventional puddled transplanted rice production faces increasing challenges due to declining groundwater resources, labour shortages, rising cultivation costs and concerns regarding soil sustainability. Under these circumstances, dry-direct seeded rice (dry-DSR) has emerged as a promising alternative to conventional transplanting because it eliminates nursery raising and puddling, reduces labour requirements and offers opportunities to improve water and energy-use efficiency. Furthermore, dry-DSR facilitates timely crop establishment and mechanization, making it particularly relevant under changing climatic conditions and resource-constrained agricultural systems. Nevertheless, its successful adoption requires appropriate agronomic management to ensure satisfactory crop establishment, vigorous vegetative growth and optimum productivity (Saha et al., 2021; Sagare et al., 2020; Pratap et al., 2021). Water availability and irrigation scheduling are important factors influencing the growth and development of dry-DSR. Unlike puddled transplanted rice, dry-DSR is established under aerobic soil conditions during the initial stages, making crop growth highly dependent on adequate soil moisture. Water deficit during early crop establishment may adversely affect seedling emergence, plant height, tiller production, leaf development and dry matter accumulation. Conversely, excessive or poorly timed irrigation may influence soil aeration, nutrient availability and crop–weed interactions. Therefore, appropriate irrigation scheduling is essential for maintaining favourable soil moisture conditions during critical crop growth stages and improving resource-use efficiency. Previous investigations have demonstrated that irrigation scheduling significantly influences plant height, tiller density, leaf area index, dry matter accumulation and yield attributes of direct-seeded rice. Narolia et al. (2014) reported that irrigation at 100% cumulative pan evaporation improved several growth and yield parameters compared with lower irrigation schedules. Similarly, Singh et al. (2022) demonstrated that the timing of the first irrigation considerably influenced the growth and productivity of direct-seeded rice. Weed infestation is one of the major biotic constraints limiting the growth and productivity of dry-DSR. Unlike transplanted rice, where established seedlings initially possess a competitive advantage over weeds, rice and weed seedlings emerge simultaneously in direct-seeded fields, resulting in intense competition for light, water, nutrients and growing space. The occurrence of diverse weed flora comprising grasses, sedges and broad-leaved weeds further complicates crop management. Uncontrolled weed growth during the early vegetative phase can substantially restrict tillering, leaf expansion and biomass accumulation, ultimately reducing crop productivity. Saha et al. (2021) reported substantial yield reduction under uncontrolled weed conditions in dry-DSR, emphasizing the importance of effective weed management. Similarly, Hashim et al. (2022) observed that sequential herbicide application effectively suppressed mixed weed flora and improved plant height, effective tiller production and other yield attributes of direct-seeded rice.

Chemical weed management, particularly the sequential application of pre-emergence (PRE) and post-emergence (POST) herbicides, has become an important component of dry-DSR production systems. PRE herbicides suppress the initial flush of weeds, whereas POST herbicides control subsequent weed emergence and established weeds belonging to different botanical groups. Integrating herbicides with appropriate crop and water management practices can provide prolonged weed suppression and minimize competition during critical growth stages. Hashim et al. (2022) reported that sequential application of pendimethalin followed by a tank mixture of bispyribac-sodium and pyrazosulfuron improved plant height, effective tillers and grain yield in dry-DSR. Likewise, Dhillon et al. (2026) demonstrated that sequential herbicide application improved weed suppression and supported better crop productivity in dry direct-seeded basmati rice. Importantly, irrigation scheduling and weed management are interrelated components of dry-DSR production because their interaction can influence crop establishment, herbicide performance and weed suppression. Soil moisture conditions following herbicide application may affect herbicide activation, availability and movement within the soil, while irrigation timing also determines the moisture environment for crop and weed growth. Inadequate moisture may restrict crop growth and reduce the effectiveness of certain soil-applied herbicides, whereas appropriately timed irrigation can support crop establishment and herbicide performance. Therefore, synchronizing irrigation with herbicide application is important for maintaining favourable conditions for crop growth while minimizing weed interference. Previous studies have indicated that irrigation timing and herbicidal treatments significantly influence plant height, dry matter accumulation, leaf area index and yield attributes of direct-seeded rice (Singh et al., 2022; Narolia et al., 2014). Despite the growing interest in dry-DSR, information regarding the combined influence of irrigation timing and weed management on crop growth remains relatively limited, particularly under the agro-climatic conditions of eastern India. Therefore, the present investigation was undertaken to evaluate the individual and interactive effects of irrigation scheduling and weed management practices on the growth performance of dry-DSR, with the objective of identifying suitable combinations for improving crop growth and resource-use efficiency under the agro-climatic conditions of Odisha.

2. MATERIAL AND METHODS

A two-year field experiment was conducted during the Rabi seasons of 2024–25 and 2025–26 at the Agronomy Main Research Farm, Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, India (20°15′ N, 85°57′ E; 25.9 m above mean sea level). The soil was sandy loam, with a pH of 6.3, organic carbon of 0.35%, and available N, P and K of 309.3, 13.11 and 160 kg ha^{-1}, respectively. A pre-emergence herbicide mixture of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG was uniformly applied at 615 g a.i. ha^{-1} immediately after sowing in all experimental plots. The main-plot factor consisted of four irrigation schedules relative to the pre-emergence herbicide application, viz., I1: immediate irrigation after sowing and followed by pre-emergence herbicide application on the same day, I2: irrigation at 1 day after sowing (1 DAS), I3: irrigation at 3 DAS, I4: irrigation at 5 DAS. The sub-plot factor comprised five weed management practices, namely 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; and W_5: weed-free maintained manually throughout the crop season. The experiment was laid out in a split-plot design with three replications, comprising four irrigation schedules (0, 1, 3 and 5 days after pre-emergence herbicide application) as main-plot treatments and five weed management practices as sub-plot treatments. Dry-direct seeded rice cultivar 'Kalinga Dhan 1201' was sown on 2 December in both years at 20 × 10 cm spacing. Pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG was applied at 615 g ha^{-1} immediately after sowing, while respective post-emergence herbicide treatments were applied at 25 days after sowing (DAS). Recommended fertilizer doses of 80:60:40 kg N–P_2O_5–K_2O ha^{-1} and 5 kg Zn ha^{-1} were applied uniformly. Plant height, number of tillers and number of leaves were recorded at different crop growth stages from five randomly selected representative hills in each plot. Plant height was measured from the soil surface to the tip of the longest fully extended leaf during vegetative stages and to the tip of the panicle during reproductive stages using a metre scale, and expressed in centimeters. The total number of tillers emerging from each selected hill was counted manually and expressed as tillers m^{-2} (converted from hill counts). Similarly, the number of fully developed leaves on each selected hill was counted manually, excluding completely dried and senescent leaves, and expressed as leaves $hill^{-1}$. The mean values of all three parameters were calculated for each treatment at the respective observation stages. Data were subjected to ANOVA appropriate for the split-plot design, and treatment means were compared using the critical difference at (P = 0.05). The present manuscript reports plant height (20 and 60 DAS), number of leaves $hill^{-1}$ (40 DAS, 60 DAS and harvest) and tiller production m^{-2} (20 and 60 DAS) as its distinct contributions from the field experiment.

3. RESULTS

3.1 Plant height at different growth stages

Irrigation schedule had a significant effect on plant height at both growth stages in 2024-25, 2025-26 and the pooled analysis (Table 1; Fig. 1a). At 20 DAS, pooled plant height ranged from 19.6 cm under I_4 (5 DAS) to 23.3 cm under I_2 (1 DAS). I_2 was statistically at par with I_1 (0 DAS; 23.0 cm), since the difference of 0.3 cm was well below the CD of 1.2. I_2 was significantly superior to I_3 (21.8 cm) and I_4, producing 6.9% and 18.9% taller plants respectively. I_1 was significantly taller than I_4 (by 17.3%), and its advantage of 5.5% over I_3 was equal to the CD, which makes it only marginally significant. I_3 was also significantly taller than I_4, by 11.2%. In the individual years, the 1.5 cm advantage of I_2 over I_3 was smaller than the CD (1.9 and 1.8 cm), so it became significant only in the pooled data. At 60 DAS the trend was the same. Pooled plant height was highest under I_2 (46.0 cm), followed by I_1 (45.5 cm), I_3 (43.1 cm) and I_4 (41.8 cm). I_2 and I_1 were at par (difference of 0.5 cm against a CD of 0.8). I_2 exceeded I_3 by 6.7% and I_4 by 10.0%, while I_1 exceeded them by 5.6% and 8.9%. I_3 was significantly taller than I_4 by 3.1%. Delaying irrigation to 3 and 5 DAS therefore reduced plant height at both stages. Weed management treatments also influenced plant height significantly (Table 1; Fig. 1b). At 20 DAS, the weed-free treatment (W_5) recorded the highest pooled height (26.6 cm), significantly more than all other treatments. It exceeded W_3 by 19.3%, W_1 by 21.5%, W_2 by 22.0% and the weedy check (W_4) by 53.8%. Among the herbicide treatments, W_3 (22.3 cm), W_1 (21.9 cm) and W_2 (21.8 cm) were statistically at par, as the largest difference of 0.5 cm was below the CD of 1.2. All three were significantly taller than the weedy check (17.3 cm), by 28.9%, 26.6% and 26.0% respectively. Compared with the weed-free treatment, the weedy check showed a 35.0% reduction in plant height. At 60 DAS, every pairwise difference between weed management treatments exceeded the CD of 1.0, so all treatments differed significantly, in the order W_5 (53.5 cm) > W_3 (48.0 cm) > W_2 (44.7 cm) > W_1 (40.9 cm) > W_4 (33.4 cm). The weed-free treatment was 60.2% taller than the weedy check, 30.8% taller than W_1, 19.7% taller than W_2 and 11.5% taller than W_3. Among the herbicide treatments, W_3 gave 43.7% more height than the weedy check, 17.4% more than W_1 and 7.4% more than W_2. W_2 exceeded W_1 by 9.3% and the weedy check by 33.8%, and W_1 exceeded the weedy check by 22.5%. W_3 reached 89.7% of the weed-free plant height, whereas the weedy check was 37.6% shorter than the weed-free treatment. The interaction between irrigation schedule and weed management (I × W) was significant at both growth stages in both years and in the pooled analysis. This indicates that the response of plant height to a weed management treatment depended on the irrigation schedule. Plant height was slightly greater in 2025-26 than in 2024-25, by about 0.5 to 1.0 cm (roughly 2 to 4%). The ranking of treatments was the same in both years, which supports the reliability of the pooled means.

Table 1. Effect of herbicide and irrigation schedule on plant height at different growth stages

Treatments	Plant height (cm)					
	20 DAS			60 DAS		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
Irrigation (Main plot)						
I_1 (0 DAS)	22.5	23.5	23.0	45.0	46.0	45.5

Treatments	Plant height (cm)					
	20 DAS			60 DAS		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
I_2 (1 DAS)	23.0	23.6	23.3	45.6	46.5	46.0
I_3 (3 DAS)	21.5	22.1	21.8	42.7	43.6	43.1
I_4 (5 DAS)	19.3	19.9	19.6	41.3	42.2	41.8
SEm (±)	0.53	0.52	0.37	0.40	0.36	0.27
CD (p=0.05)	1.9	1.8	1.2	1.4	1.3	0.8
Weed Management (Sub plot)						
W_1 (Fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha (Tank-mix))	21.7	22.2	21.9	40.5	41.4	40.9
W_2 (Bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl (RM) 43 g/ha)	21.4	22.1	21.8	44.2	45.2	44.7
W_3 (Florpyrauxifen-benzyl 2.13% w/w + cyhalofop-butyl 10.64% w/w EC (RM) 150 g/ha)	22.0	22.6	22.3	47.5	48.4	48.0
W_4 (Weedy Check)	17.0	17.6	17.3	33.0	33.9	33.4
W_5 (Weed Free)	26.3	26.9	26.6	53.0	54.0	53.5
SEm (±)	0.61	0.61	0.43	0.49	0.48	0.34
CD (p=0.05)	1.8	1.8	1.2	1.4	1.4	1.0
Interaction (I x W)	S	S	S	S	S	S

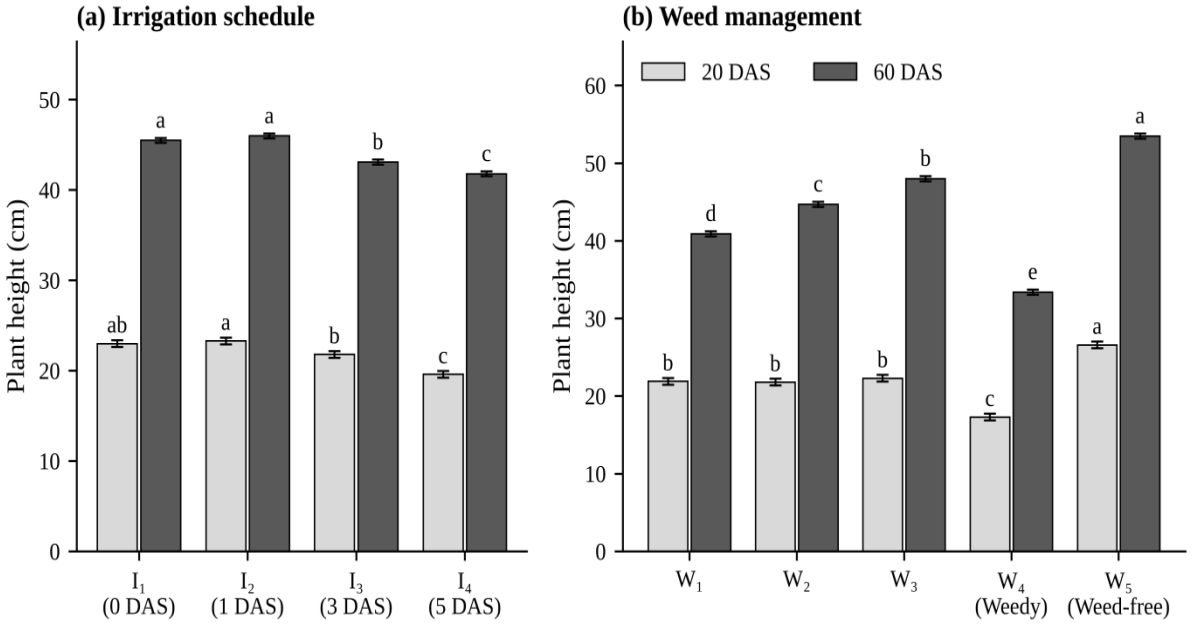


Fig. 1. Effect of irrigation schedule (a) and weed management (b) on plant height at 20 and 60 DAS. Bars show pooled means ± SEm; bars with the same letter within a growth stage do not differ significantly according to Duncan's Multiple Range Test (P = 0.05). W_1, fenoxaprop-ethyl + ethoxysulfuron; W_2, bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl; W_3, florpyrauxifen-benzyl + cyhalofop-butyl; W_4, weedy check; W_5, weed-free.

3.2 Number of leaves hill-1 at different growth stages

Irrigation schedule had a significant effect on leaf number hill^{-1} at 40 DAS, 60 DAS and at harvest in both years and in the pooled analysis (Table 2; Fig. 2a). At 40 DAS, pooled leaf number ranged from 35.55 under I_4 (5 DAS) to 40.10 under I_2 (1 DAS). I_2 was statistically at par with I_1 (0 DAS; 39.45), since the difference of 0.65 was below the CD of 1.02. Both were significantly superior to I_3 (37.90) and I_4. I_2 produced 5.8% and 12.8% more leaves than I_3 and I_4 respectively, and I_1 produced 4.1% and 11.0% more. I_3 also had 6.6% more leaves than I_4, a significant difference. At 60 DAS, I_2 recorded the highest leaf number (53.75), followed by I_1 (53.00), I_3 (51.25) and I_4 (48.00). I_2 and I_1 were at par (difference of 0.75 against a CD of 1.35), while both were significantly better than I_3 and I_4. I_2 exceeded I_3 by 4.9% and I_4 by 12.0%, and I_1 exceeded them by 3.4% and 10.4%. I_3 was significantly higher than I_4 by 6.8%. At harvest, the same order was maintained: I_2 (48.25), I_1 (47.50), I_3 (45.90) and I_4 (43.15). I_2 and I_1 were at par (difference of 0.75 against a CD of 1.22). I_2 exceeded I_3 by 5.1% and I_4 by 11.8%, I_1 exceeded them by 3.5% and 10.1%, and I_3 exceeded I_4 by 6.4%. Delaying irrigation to 5 DAS therefore reduced leaf number by 10.6 to 11.3% relative to irrigation at 1 DAS at all three stages. Weed management also influenced leaf number hill^{-1} significantly (Table 2; Fig. 2b). At 40 DAS, the weed-free treatment (W_5) recorded the highest pooled leaf number (41.05), followed closely by W_3 (40.65). The two were statistically at par (difference of 0.40 against a CD of 1.10), and W_3 reached 99.0% of the weed-free value. W_3 was significantly superior to W_2 (39.40) and W_1 (38.50), with gains of 3.2% and 5.6%, whereas W_2 and W_1 did not differ significantly (difference of 0.90, or 2.3%). All weed control treatments were significantly better than the weedy check (W_4; 35.70). W_5, W_3, W_2 and W_1 exceeded it by 15.0%, 13.9%, 10.4% and 7.8% respectively, and the weedy check had 13.0% fewer leaves than the weed-free treatment. At 60 DAS, W_5 (54.90) and W_3 (54.50) were again at par (difference of 0.40 against a CD of 1.43), with W_3 reaching 99.3% of the weed-free value. Both were significantly higher than W_2 (52.60) and W_1 (51.50). W_3 exceeded W_2 by 3.6% and W_1 by 5.8%, and W_5 exceeded them by 4.4% and 6.6%. W_2 and W_1 were at par (difference of 1.10, or 2.1%). The weedy check (48.15) was significantly lowest, with W_5, W_3, W_2 and W_1 exceeding it by 14.0%, 13.2%, 9.2% and 7.0%, and with a 12.3% reduction in leaf number relative to the weed-free treatment. At harvest, the pattern was the same. W_5 (48.90) and W_3 (48.55) were at par (difference of 0.35 against a CD of 1.28; W_3 reached 99.3% of W_5) and significantly superior to W_2 (47.25) and W_1 (46.20). W_3 exceeded W_2 by 2.8% and W_1 by 5.1%, while W_5 exceeded them by 3.5% and 5.8%. W_2 and W_1 were at par (difference of 1.05, or 2.3%). The weedy check (43.25) recorded significantly the lowest leaf number. W_5, W_3, W_2 and W_1 exceeded it by 13.1%, 12.3%, 9.2% and 6.8%, and the weedy check lost 11.6% of leaves compared with the weed-free treatment. The interaction between irrigation schedule and weed management (I × W) was significant at all three stages in both years and in the pooled analysis. This indicates that the effect of a weed management treatment on leaf number depended on the irrigation schedule. Leaf number was slightly higher in 2025-26 than in 2024-25, by about 0.6 to 0.8 leaves hill^{-1}. The treatment ranking was the same in both years, which supports the reliability of the pooled means.

Table 2. Effect of herbicide and irrigation schedule on number of leaves hill⁻¹ at different growth stages

Treatments	Leaf number hill-1								
	40 DAS			60 DAS			At Harvest		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
Irrigation (Main plot)									
I_1 (0 DAS)	39.1	39.8	39.45	52.6	53.4	53.00	47.2	47.8	47.5
I_2 (1 DAS)	39.8	40.4	40.1	53.4	54.1	53.75	47.9	48.6	48.25
I_3 (3 DAS)	37.6	38.2	37.9	50.9	51.6	51.25	45.6	46.2	45.9
I_4 (5 DAS)	35.2	35.9	35.55	47.6	48.4	48	42.8	43.5	43.15
SEm (±)	0.461	0.482	0.333	0.612	0.651	0.441	0.542	0.571	0.392
CD (P=0.05)	1.42	1.48	1.02	1.88	2.0	1.35	1.67	1.76	1.22
Weed management (Sub plot)									
W_1 (Fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha (Tank-mix))	38.2	38.8	38.5	51.1	51.9	51.5	45.9	46.5	46.2
W_2 (Bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl (RM) 43 g/ha)	39.1	39.7	39.4	52.2	53	52.6	46.9	47.6	47.25
W_3 (Florpyrauxifen-benzyl 2.13% w/w + cyhalofop-butyl 10.64% w/w EC (RM) 150 g/ha)	40.3	41	40.65	54.1	54.9	54.5	48.2	48.9	48.55
W_4 (Weedy Check)	35.4	36	35.7	47.8	48.5	48.15	42.9	43.6	43.25
W_5 (Weed Free)	40.7	41.4	41.05	54.5	55.3	54.9	48.6	49.2	48.9
SEm (±)	0.523	0.554	0.382	0.681	0.712	0.492	0.603	0.641	0.442
CD (P=0.05)	1.50	1.58	1.10	1.96	2.05	1.43	1.74	1.84	1.28
I x W	S	S	S	S	S	S	S	S	S

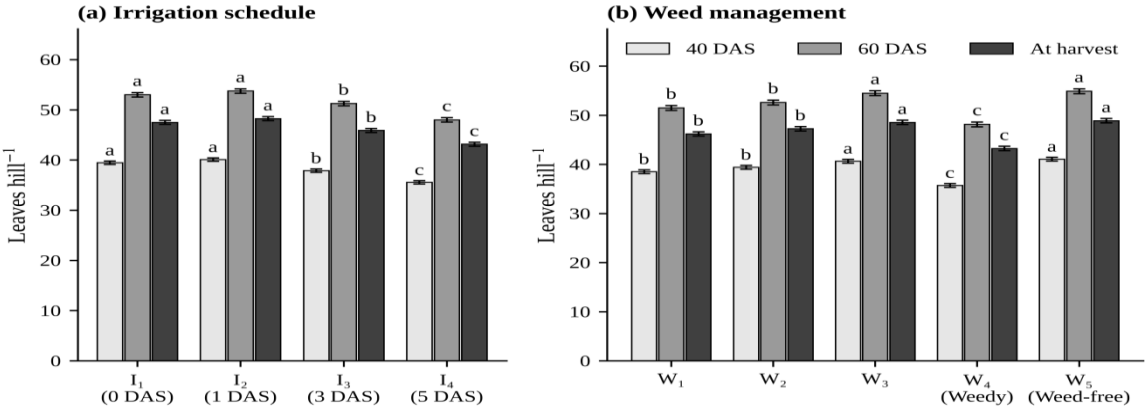


Fig. 2. Effect of irrigation schedule (a) and weed management (b) on number of leaves hill⁻¹ at 40 DAS, 60 DAS and harvest. Bars show pooled means ± SEm; bars with the same letter within a growth stage do not differ significantly according to Duncan's Multiple Range Test (P = 0.05). W_1, fenoxaprop-ethyl + ethoxysulfuron; W_2, bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl; W_3, florpyrauxifen-benzyl + cyhalofop-butyl; W_4, weedy check; W_5, weed-free.

3.3 No. of tillers production m-2 at different growth stages

Irrigation schedule significantly influenced tiller production at both growth stages in both years and in the pooled analysis (Table 3; Fig. 3a). At 20 DAS, pooled tiller number was highest under I_2 (1 DAS; 88.8), followed by I_1 (0 DAS; 88.0), I_3 (74.3) and I_4 (68.1). I_2 and I_1 were statistically at par, since their difference of 0.8 was far below the CD of 3.4, and both

were significantly superior to I_3 and I_4. I_2 produced 19.5% and 30.4% more tillers than I_3 and I_4 respectively, while I_1 produced 18.4% and 29.2% more. I_3 also had 9.1% more tillers than I_4, a significant difference (6.2 against a CD of 3.4). Irrigation at 5 DAS therefore reduced tiller number by 23.3% compared with irrigation at 1 DAS. At 60 DAS, I_2 (277.4) and I_1 (275.6) were again at par (difference of 1.8 against a CD of 7.2), and both were significantly superior to I_3 (259.9) and I_4 (254.1). I_2 exceeded I_3 by 6.7% and I_4 by 9.2%, and I_1 exceeded them by 6.0% and 8.5%. Unlike at 20 DAS, the difference between I_3 and I_4 (5.8, or 2.3%) was below the CD of 7.2 and was not significant. The gap between the irrigation treatments narrowed with crop growth, from 30.4% at 20 DAS to 9.2% at 60 DAS between I_2 and I_4. Weed management did not affect tiller number significantly among the herbicide treatments and the weedy check at 20 DAS (Table 3; Fig. 3b). The weed-free treatment (W_5) recorded the highest pooled tiller number (102.2), significantly more than all other treatments. It exceeded W_3 and W_4 (both 74.4) by 37.4%, W_1 (74.1) by 37.9% and W_2 (74.0) by 38.1%. The four remaining treatments (W_1, W_2, W_3 and W_4) were statistically at par, with a maximum difference of only 0.4 against a CD of 2.4. The weedy check and the herbicide treatments each had 27.2 to 27.6% fewer tillers than the weed-free treatment. At 60 DAS, all weed management treatments differed significantly, as every pairwise difference exceeded the CD of 5.5. The order was W_5 (303.7) > W_3 (294.9) > W_2 (282.5) > W_1 (273.6) > W_4 (175.8). W_5 produced 72.8% more tillers than the weedy check, 11.0% more than W_1, 7.5% more than W_2 and 3.0% more than W_3. Among the herbicide treatments, W_3 gave 67.7% more tillers than the weedy check, 7.8% more than W_1 and 4.4% more than W_2, and it reached 97.1% of the weed-free tiller number. W_2 exceeded W_1 by 3.3% and the weedy check by 60.7%, and W_1 exceeded the weedy check by 55.6%. The weedy check recorded by far the lowest tiller number, 42.1% lower than the weed-free treatment, showing the severe effect of uncontrolled weed competition on tillering. The interaction between irrigation schedule and weed management (I × W) was significant at both stages in both years and in the pooled analysis, which indicates that the effect of weed management on tiller production depended on the irrigation schedule. Tiller number differed very little between years: the 2025-26 means were only 0.0 to 0.1 higher at 20 DAS and about 0.7 to 1.0 higher at 60 DAS (0.2 to 0.6%). The treatment ranking was identical in both years, which supports the reliability of the pooled means.

Table 3. Effect of herbicide and irrigation schedule on number of tillers m^{-2} at different growth stages

Treatments	20 DAS			60 DAS		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
Irrigation (Main plot)						
I_1 (0 DAS)	88.0	88.1	88.0	275.2	276.1	275.6
I_2 (1 DAS)	88.7	88.8	88.8	276.9	277.9	277.4
I_3 (3 DAS)	74.3	74.3	74.3	259.5	260.3	259.9
I_4 (5 DAS)	68.1	68.1	68.1	253.6	254.5	254.1
SEm (±)	1.55	1.55	1.10	3.27	3.29	2.33
CD (p=0.05)	5.4	5.4	3.4	11.3	11.4	7.2
Weed management (Sub plot)						
W_1 (Fenoxaprop-ethyl 67 g/ha + ethoxysulfuron 18 g/ha (Tank-mix))	74.1	74.1	74.1	273.2	274.0	273.6
W_2 (Bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl (RM) 43 g/ha)	74.0	74.0	74.0	282.0	282.9	282.5
W_3 (Florpyrauxifen-benzyl 2.13% w/w + cyhalofop-butyl 10.64% w/w EC (RM) 150 g/ha)	74.3	74.4	74.4	294.5	295.2	294.9
W_4 (Weedy Check)	74.3	74.4	74.4	175.3	176.3	175.8

Treatments	20 DAS			60 DAS		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
W_5 (Weed Free)	102.2	102.2	102.2	303.3	304.0	303.7
SEm (±)	1.19	1.19	0.84	2.72	2.72	1.91
CD (p=0.05)	3.4	3.4	2.4	7.8	7.8	5.5
Interaction (I x W)	S	S	S	S	S	S

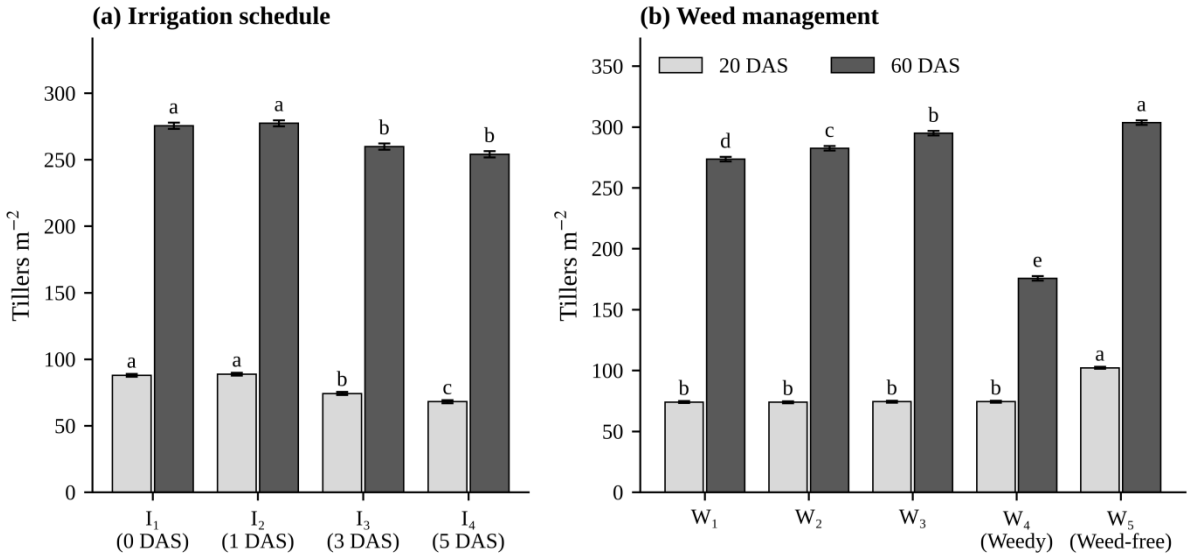


Fig. 3. Effect of irrigation schedule (a) and weed management (b) on number of tillers m^{-2} at 20 and 60 DAS. Bars show pooled means ± SEm; bars with the same letter within a growth stage do not differ significantly according to Duncan's Multiple Range Test (P = 0.05). W_1, fenoxaprop-ethyl + ethoxysulfuron; W_2, bispyribac-sodium + chlorimuron-ethyl + metsulfuron-methyl; W_3, florpyrauxifen-benzyl + cyhalofop-butyl; W_4, weedy check; W_5, weed-free.

4. DISCUSSION

4.1 Effect of irrigation scheduling and weed management on plant height

Plant height reflects the combined effects of water availability, nutrient acquisition, photosynthetic activity and competition for growth resources. Irrigation scheduling and weed management significantly influenced plant height at 20 and 60 DAS. Irrigation at 1 DAS (I_2), statistically at par with irrigation at 0 DAS (I_1), gave the greatest height. Adequate soil moisture soon after sowing favours seed imbibition, germination, root development and nutrient uptake, which support cell division and elongation. Delayed irrigation (I_3, 3 DAS; I_4, 5 DAS) probably restricted early root activity and nutrient acquisition, with I_4 recording the lowest height at both stages. The small difference between I_1 and I_2 shows that immediate irrigation had no clear advantage over irrigation at 1 DAS. Because plant water status was not measured, these differences reflect irrigation timing and not direct evidence of water stress. The response agrees with Kumawat et al. (2017), who reported greater height and growth attributes of direct-seeded rice under schedules that maintained favourable soil moisture, and with Narolia et al. (2014), who reported significant effects of irrigation scheduling on plant height and dry-matter accumulation. The optimum timing nevertheless depends on soil, weather and seedbed moisture, so the result should be read in the context of this experiment. The weed-free treatment (W_5) consistently recorded the greatest height. It was 53.8% and 60.2% taller than the weedy check (W_4) at 20 and 60 DAS, respectively, showing that the damage from weed competition increased as the crop grew. In direct-seeded rice, weeds emerge with the crop and compete for moisture, nutrients, light and space, which restricts leaf development and photosynthates accumulation. Among the herbicide treatments, W_3 gave the greatest height, followed by W_2 and W_1. The three were at par at 20 DAS but separated at 60 DAS, indicating that differences in weed suppression became clearer at later vegetative stages. W_3 attained 89.7% of weed-free height at 60 DAS, probably because it suppressed the diverse weed flora more effectively. It did not match W_5, possibly because of shorter or less complete weed suppression and residual weed competition. Similar improvements in growth and productivity through herbicide-based weed management in direct-seeded rice were reported by earlier researchers. Singh et al. (2012) identified the first 40 DAS as the critical period of crop–weed competition, stressing the need for a weed-free environment during early development. Hashim et al. (2022) reported that effective herbicidal control

reduced weed density and biomass and improved the productivity of dry direct-seeded rice. Hashim et al. (2024), in their review of weed management strategies in direct-seeded rice, highlighted the importance of choosing weed-control practices according to weed flora and the critical period of competition. The irrigation × weed management (I × W) interaction was significant at both stages in each year and in the pooled analysis, so the effect of weed management depended on irrigation timing. The specific combinations responsible must be identified from the interaction means and critical differences, not inferred from the main effects. Plant height was marginally greater in 2025–26 than in 2024–25, but the treatment ranking was consistent across years, so the responses were reproducible. The year difference cannot be tied to any environmental factor without weather and crop-growth data. Overall, irrigation at 1 DAS (I_2), comparable with I_1, favoured plant height, whereas delaying irrigation to 3 or 5 DAS reduced it. Weed-free conditions gave the maximum height, and W_3 was the most effective herbicide treatment. Timely irrigation combined with effective weed management therefore promotes early and sustained vegetative growth in dry direct-seeded rice.

4.2 Effect of irrigation scheduling and weed management on number of leaves hill^{-1}

Leaf number reflects vegetative development and canopy establishment, and it is influenced by soil moisture, nutrient uptake, crop establishment and weed competition. Irrigation scheduling significantly affected leaves hill^{-1} at 40 DAS, 60 DAS and harvest. I_2 (1 DAS) consistently recorded the most leaves, statistically at par with I_1, indicating that irrigation at 1 DAS supported leaf development as well as immediate irrigation. Delayed irrigation (I_3, I_4) gave fewer leaves, and I_4 reduced leaf number by about 11% relative to I_2 at all three stages. This shows that the effect of early moisture availability persisted beyond seedling establishment and influenced canopy development. Adequate moisture maintains cell turgidity, nutrient transport and the metabolic activity needed for leaf initiation and expansion. The importance of appropriate irrigation management for dry-seeded rice is supported by Sudhir-Yadav et al. (2012), who examined the influence of irrigation scheduling on land and water productivity. Weed management also significantly affected leaf number at all three stages. W_5 recorded the most leaves hill^{-1}, statistically at par with W_3, which attained 99.0–99.3% of the weed-free leaf number. W_3 therefore minimised crop–weed competition and maintained leaf development close to that under complete weed control. W_5 produced 13.1–15.0% more leaves hill^{-1} than the weedy check (W_4), whose lower leaf number reflects prolonged competition from mixed weed flora for moisture, nutrients, light and space. In dry direct-seeded rice this competition is especially damaging because crop and weeds emerge together. Among the herbicide treatments, W_3 was significantly superior to W_1 and W_2 at 40 DAS, and its advantage was greatest at 60 DAS and narrower at harvest. W_1 and W_2 were statistically comparable at all stages. These observations are supported by Narolia et al. (2014), who reported improved growth attributes and productivity of direct-seeded rice with sequential pendimethalin followed by bispyribac-sodium. Choudhary and Dixit (2021) showed that sequential herbicide application effectively suppressed weed density and biomass in dry direct-seeded rice and improved productivity. Hashim et al. (2022) reported improved growth and yield attributes through effective herbicidal management of complex weed flora. These studies evaluated overall growth and yield attributes rather than leaf number specifically, but they support the view that effective weed suppression improves the growth environment and vegetative development. The I × W interaction was significant at 40 DAS, 60 DAS and harvest, showing that the leaf response to weed management varied with irrigation timing. The superior combination cannot be identified from the significance alone and must be read from the treatment-combination means and critical differences. Leaf number was slightly greater in 2025–26, but the consistent treatment ranking shows the responses were stable across seasons. No specific environmental cause can be given without supporting observations. In summary, irrigation at 1 DAS (I_2), comparable with I_1, maintained more leaves hill^{-1} throughout crop development, and W_5 and W_3 were statistically comparable. The poor performance of the weedy check shows the adverse effect of uncontrolled weeds. Timely irrigation with effective weed management, particularly W_3, is therefore important for leaf development and canopy establishment in dry direct-seeded rice.

4.3 Effect of irrigation scheduling and weed management on tiller production

Tiller number during the vegetative phase largely determines the potential number of productive panicles, and it is influenced by soil moisture, nutrient acquisition, light interception and weed competition. Irrigation scheduling significantly influenced tiller production at 20 and 60 DAS in each year and in the pooled analysis. I_2 (1 DAS) recorded the most tillers, at par with I_1 at both stages, so delaying the first irrigation by one day did not adversely affect tiller establishment. The greater tillering under I_1 and I_2 than under I_3 and I_4 may be due to favourable early moisture, which supports root development, nutrient uptake and tiller bud initiation. The effect of delay was greatest at 20 DAS, when I_4 recorded 23.3% fewer tillers than I_2. The gap narrowed to 9.2% at 60 DAS, suggesting partial compensation once moisture became available, although I_2 and I_1 retained a significant advantage. Narolia et al. (2014) similarly found that irrigation scheduling significantly influenced tiller production per unit area, with irrigation at 100% cumulative pan evaporation giving more tillers than the comparatively water-deficient schedule. Kumawat et al. (2017) reported higher effective tiller production under irrigation maintained at saturation, statistically comparable with irrigation at 10-kPa soil-water tension. Weed management strongly influenced tillering, particularly at 60 DAS. At 20 DAS, W_5 recorded significantly more tillers than all other treatments, while the herbicide treatments and the weedy check were at par, so differences in weed suppression had not yet translated into tillering differences. At 60 DAS all treatments differed significantly, in the order $W_5 > W_3 > W_2 > W_1 > W_4$. The weedy check produced 42.1% fewer tillers than the weed-free treatment, showing how prolonged competition for nutrients, moisture, light and space restricts tillering. W_3 was the best herbicide treatment and attained 97.1% of weed-free tiller number, probably because of more effective suppression of the weed flora, though W_5 remained significantly higher. These findings agree with Narolia et al. (2014), who reported that sequential pendimethalin followed by bispyribac-sodium improved tillers per square metre and other yield attributes over the weedy check. Hashim et al. (2023) reported that effective sequential herbicide application improved effective tillers and other yield-contributing

attributes in dry direct-seeded rice. Pradhan et al. (2023) showed that hand weeding and suitable post-emergence herbicides improved tiller production and yield attributes. The I × W interaction was significant at both stages in each year and in the pooled analysis, indicating that the effect of weed management on tillering varied with irrigation timing. Its magnitude and direction should be interpreted from the I × W means and critical differences. Tiller production differed negligibly between years and the treatment ranking was consistent, supporting the reliability of the pooled results. In summary, irrigation at 1 DAS (I_2), comparable with I_1, favoured tillering, while W_5 gave the maximum tiller number and W_3 was the most effective herbicide treatment. The marked reduction under delayed irrigation and uncontrolled weeds shows the importance of timely moisture and effective weed management for tiller development and yield potential in dry direct-seeded rice.

5. CONCLUSION

Irrigation scheduling and weed management significantly influenced the growth of dry direct-seeded rice. Irrigation one day after pre-emergence herbicide application (I_2), statistically comparable with immediate irrigation, produced the tallest plants, most leaves and highest tiller number, whereas delaying irrigation to 3-5 days reduced growth. Weed-free conditions gave maximum growth, and florpyrauxifen-benzyl + cyhalofop-butyl (W_3) was the most effective herbicide treatment, reaching 89.7-99.3% of weed-free performance. Uncontrolled weeds reduced plant height by 37.6% and tillers by 42.1% at 60 DAS.

6. ACKNOWLEDGEMENTS

The authors extend their profound gratitude to the Vice-Chancellor of the Odisha University of Agriculture and Technology, Bhubaneswar, for his continuous encouragement and for providing the essential institutional facilities throughout the research period. His invaluable guidance and steadfast support were pivotal to the successful execution and completion of this study.

7. Authors' contributions

The study was conceptualized by Dharani Dhar Pradhan and Suchismita Tripathy, while experimental design and methodological development were undertaken by Rabiratna Dash and Suchismita Tripathy. Field experiments, data collection and curation, and laboratory investigations were collaboratively carried out by Dharani Dhar Pradhan, Suchismita Tripathy, Anupama Baliarsingh, A.C. Dash, A.K. Sethy, Rajkumari Bhol, and G. Prameela. Statistical analyses, data interpretation, visualization, and validation were performed by Dharani Dhar Pradhan, A.K. Sethy, A.C. Dash, S. Karubakee, and Arunima Goswami. The initial manuscript was drafted by Dharani Dhar Pradhan. Technical supervision, critical evaluation, manuscript review, and substantial editorial contributions were provided by P.J. Mishra, A.K. Sethy, Suchismita Tripathy, Narayan Panda, Soumya Mohanty, Rameswar Jena and Susree Snigdha Das. Project supervision, coordination, administration, and final manuscript evaluation were undertaken by Rabiratna Dash and P.J. Mishra. All authors contributed to the critical review and approved the final version of the manuscript for submission.

8. Compliance with ethical standards

The study was carried out in compliance with relevant institutional guidelines and applicable ethical standards. The research involved field-based experimentation on rice, with all experimental activities performed in accordance with established agronomic practices and institutional protocols for agricultural field research.

9. Conflict of interest:

The authors declare that they have no competing financial or personal interests that could have influenced the research or its reporting. The data underlying the findings of this study can be obtained from the corresponding author upon reasonable request. During manuscript preparation, generative AI tools, namely ChatGPT (OpenAI) and Claude AI (Anthropic), were employed exclusively for language refinement, grammatical corrections, and textual editing. All AI-assisted modifications were carefully reviewed and revised by the authors, who accept full responsibility for the accuracy, originality, and integrity of the final manuscript. No AI tools were used for data generation, statistical analysis, or interpretation of the experimental results.

10. Ethical issues:

The field study involved personnel engaged in routine agricultural activities, such as crop establishment, irrigation management, herbicide application, weed control, and experimental data collection. However, the research did not involve the recruitment of human participants, nor was any personal, medical, or biological information obtained from any individual.

REFERENCE

1. Choudhary, V.K. and Dixit, A. (2021). Bio-efficacy of sequential herbicide application for weed management in dry direct seeded rice. The Indian Journal of Agricultural Sciences, 91(1): 79–83. https://doi.org/10.56093/ijas.v91i1.110930
2. Dhillon, B.S., Kaur, G., Sharma, K.P., Kaur, R., Sidhu, N. and Kumar, R.M. (2026). Crop establishment and weed management effects on weed flora and yield of dry direct-seeded basmati rice (Oryza sativa) in the north-western Indo-Gangetic plains. The Indian Journal of Agricultural Sciences, 96(5): 673–680. https://doi.org/10.56093/ijas.v96i5.176042
3. Hashim, M., Singh, V.K., Singh, K.K. and Dhar, S. (2022). Herbicidal weed-management options for dry direct-seeded rice (Oryza sativa) in North-Eastern Plains of India. Indian Journal of Agronomy, 67(4): 337–342. https://doi.org/10.59797/ija.v67i4.135

4. Hashim, M., Singh, V.K., Singh, K.K., Dhar, S. and Pandey, U.C. (2024). Weed management strategies in direct seeded rice: A review. Agricultural Reviews, 45(2): 258–265. https://doi.org/10.18805/ag.R-2245
5. Kumawat, A., Sepat, S., Kumar, D., Jinger, D. and Kaur, R. (2017). Effect of irrigation scheduling on yield and water-use efficiency of direct-seeded rice (Oryza sativa L.). Annals of Agricultural Research, 38(1). https://epubs.icar.org.in/index.php/AAR/article/view/70008
6. Narolia, R.S., Singh, P., Prakash, C. and Meena, H. (2014). Effect of irrigation schedule and weed-management practices on productivity and profitability of direct-seeded rice (Oryza sativa) in South-eastern Rajasthan. Indian Journal of Agronomy, 59(3): 398–403. https://doi.org/10.59797/ija.v59i3.5616
7. Pradhan, A., Dixit, A., Keram, K.S. and Dewangan, P.K. (2023). Weed management in dry direct-seeded rice under rainfed ecology of Southern Chhattisgarh. Indian Journal of Weed Science, 55(2): 149–152. https://doi.org/10.5958/0974-8164.2023.00026.6
8. Pratap, V., Verma, S.K., Dass, A., Yadav, D.K., Jaysawal, P.K. and Madan, A. (2021). Productivity and profitability of direct-seeded rice under varying establishment methods and weed management practices. The Indian Journal of Agricultural Sciences, 91(4): 537–541. https://doi.org/10.56093/ijas.v91i4.112635
9. Sagare, D.B., Abbai, R., Jain, A., Jayadevappa, P.K., Dixit, S., Singh, A.K., Challa, V., Alam, S., Singh, U.M., Yadav, S., Sandhu, N., Kabade, P.G., Singh, V.K. and Kumar, A. (2020). More and more of less and less: Is genomics-based breeding of dry direct-seeded rice (DDSR) varieties the need of hour? Plant Biotechnology Journal. https://doi.org/10.1111/pbi.13454
10. Saha, S., Munda, S., Singh, S., Kumar, V., Jangde, H.K., Mahapatra, A. and Chauhan, B.S. (2021). Crop establishment and weed control options for sustaining dry direct seeded rice production in Eastern India. Agronomy, 11(2): 389. https://doi.org/10.3390/agronomy11020389
11. Singh, H., Sandhu, K.S. and Bansal, K.K. (2022). Effect of first irrigation scheduling and herbicides on productivity of direct-seeded rice (Oryza sativa). Indian Journal of Agronomy, 67(1): 93–96. https://doi.org/10.59797/ija.v67i1.95
12. Singh, M., Sairam, C.V., Hanji, M.B., Prabhukumar, S. and Kishor, N. (2012). Crop-weed competition and weed management studies in direct seeded rice (Oryza sativa). Indian Journal of Agronomy, 57(1): 38–42. https://doi.org/10.59797/ija.v57i1.4612
13. Sudhir-Yadav, Humphreys, E., Li, T., Gill, G. and Kukal, S.S. (2012). Evaluation of tradeoffs in land and water productivity of dry seeded rice as affected by irrigation schedule. Field Crops Research, 128: 180–190. https://doi.org/10.1016/j.fcr.2012.01.005