



RESEARCH ARTICLE

Effect of irrigation scheduling and water stress management on yield, nutrient uptake and profitability of wet-direct seeded rice (*Oryza sativa* L.) under puddled conditions

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Abstract

A field study was carried out at V.O.C Agricultural College and Research Institute, Killikulam, during the early Kar season of 2021-2022 to assess how different irrigation schedules and water stress management strategies influence profitability and nutrient uptake in direct-seeded rice (*Oryza sativa* L.) under puddled conditions. The experiment followed a split-plot design with three replications, where the main plots consisted of four irrigation treatments: Alternate wetting and drying (AWD), Irrigation based on the IW/CPE ratio, Water depletion of 15 cm using a field water tube (FWT) and Continuous flooding (Control). The subplots included four water stress management practices: Seed treatment with 1 % Pink pigmented facultative methylotrophs (PPFM) and 1 % foliar spray at critical growth stages, foliar application of paclobutrazol (50 ppm) at critical growth stages, seed treatment with arbuscular mycorrhizal (AM) fungi and soil application at 100 g m⁻² and control. The findings revealed that continuous flooding combined with 1 % PPFM application resulted in the highest grain yield (7.6 t ha⁻¹), straw yield (8.3 t ha⁻¹), nitrogen uptake (110.3 kg ha⁻¹), potassium uptake (125.7 kg ha⁻¹), net profitability (₹87950 ha⁻¹) and a benefit-cost ratio of 3.07, which was statistically comparable to the AWD method with 1 % PPFM application. These results suggest that AWD with 1 % PPFM application at critical stages is a viable alternative to continuous flooding for efficient water usage and managing water stress in direct-seeded rice.

Keywords: alternate wetting and drying; nutrient uptake and profitability; PPFM; wet seeded rice

Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the global population, particularly in Asia (1), where it serves as a primary source of carbohydrates and livelihoods for millions of smallholder farmers (2). The cultivation of rice predominantly occurs in flooded conditions. This traditional method is effective for weed control and nutrient availability, but it is highly water-intensive, leading to concerns over water use efficiency and environmental sustainability (3). The productivity of rice in India has increased to 2.8 t ha⁻¹, with increased water consumption (4). The future of rice cultivation in India hinges on efficient water management strategies like the Alternate wetting and drying (AWD) method, system of rice intensification, direct-seeded rice and precision irrigation that balance productivity with sustainability. By adopting innovative techniques, leveraging technology and implementing sound policies, India can secure rice production while conserving water resources for future generations. In response to efficient water management, direct-seeded rice (DSR) has emerged as one of the viable alternatives, offering benefits such as reduced labour, energy savings and decreased greenhouse gas emissions (5).

Water scarcity is a growing concern in rice cultivation, particularly in regions heavily reliant on groundwater and surface water resources (6). Efficient irrigation scheduling is critical to optimise water use efficiency (WUE) while maintaining or enhancing crop productivity. However, the impact of different irrigation strategies on yield, profitability and nutrient uptake in DSR under puddled conditions has not been extensively studied. Moreover, the interaction between water stress and nutrient dynamics in DSR systems remains a significant research gap. Nutrient uptake in rice is closely linked to water availability, as water stress can alter root morphology, nutrient mobility and plant physiological processes, ultimately affecting yield and profitability. DSR eliminates the need for continuous flooding, reducing water consumption by 30 %–50 % compared to traditional methods (7). Transplanting rice requires significant manual labour, whereas DSR eliminates this step, leading to 20 %–40 % labour savings. Reduced dependency on manual labour also lowers production costs, making rice farming more economically viable (8). Studies show that DSR crops mature 7–10 days earlier than transplanted rice, allowing for better crop rotation (9).

Water demand in future due to growing population and urbanisation leads to water scarcity in irrigation. Water scarcity is expected to affect approximately 20 % of irrigated rice by 2030 (10). Accordingly, some water saving techniques such as AWD, system of rice intensification, use of field water tubes and evapotranspiration irrigation have been implemented in various rice growing regions in order to make better use of water and increase water productivity, yield and profitability (11). An AWD irrigation could significantly improve water productivity in DSR without compromising yield (12). AWD reduces irrigation water use by 25 %-50 % compared to continuous flooding (13). AWD reduces methane emissions by 30 %-50 % due to periodic soil aeration, which limits anaerobic conditions favourable for methane production (14). The limitation includes that if drying periods are too long, it can cause moisture stress, leading to reduced grain filling and lower yields (15). Dry soil conditions promote weed emergence, increasing the need for herbicide application or manual weeding (16). Despite these advancements, there remains a research gap in understanding the combined effects of irrigation scheduling and water stress management on the yield, profitability and nutrient uptake of DSR under puddled conditions. This paper aims to address these gaps by systematically examining the impact of various irrigation schedules and water stress management strategies on the agronomic performance of DSR cultivated under puddled conditions.

Materials and Methods

Experimental site

This research was carried out at V.O.C Agricultural College and Research Institute, located in Killikulam, Tamil Nadu. The study area is located at 8°46' N latitude and 77°42' E longitude, with an elevation of 40 m above mean sea level. The experiment was conducted during the early Kar season of 2021-2022. The soil in the experimental area was classified as sandy clay loam, with slight salinity. The soil had a pH of 7.7, an electrical conductivity (EC) of 0.19 dS m⁻¹ and an organic carbon content of 5.9 g kg⁻¹. Pre-sowing soil analysis revealed the macronutrient contents of 238 kg ha⁻¹ of nitrogen (N), 17 kg ha⁻¹ of phosphorus (P) and 249 kg ha⁻¹ of potassium (K).

Experimental details and design

The field experiment was conducted using a split plot design with three replications. The main plot treatments comprised irrigation schedules, viz. M₁- AWD, M₂- IW/CPE ratio, M₃- FWT and M₄- control (continuous flooding). The subplots consist of various stress management practices, viz. S₁- seed treatment with 1 % PPFM + 1 % foliar spray at critical stages, S₂- foliar spray of 50 ppm paclobutrazol at critical stages, S₃- seed treatment with AM fungi + soil application at 100 g m⁻² and S₄- control. PPFM is known to produce osmoprotectants such as proline, trehalose and glycine betaine, which help in maintaining cellular water balance under drought conditions (17).

Agronomic practices

The rice variety selected for this study was ASD 16, which has a growth duration of 110-120 days. To improve drought tolerance, seed hardening was performed using 1 % potassium chloride (KCl), along with seed treatments involving PPFM and AM fungi. The treated seeds were directly sown using a drum seeder. A standardised fertiliser application rate of 150:50:50 NPK g ha⁻¹ was

applied for all treatments. The fertilisers used included urea (46 % N), single super phosphate (16 % P₂O₅) and muriate of potash (60 % K₂O). Fertilisers were applied in four split doses: urea and potash were applied at the basal stage, active tillering, panicle initiation and heading stages, whereas single super phosphate (SSP) was applied as a basal dose only. Additionally, AM fungi are pre-mixed with farmyard manure (FYM) and are incorporated into the soil before sowing and during critical growth stages at respective treatment.

Water management practices included providing light irrigation for the first seven days after sowing (DAS), followed by maintaining a 2 cm water level until 21 DAS. After this period, irrigation was applied according to the specific treatment schedules. In the AWD method, water was supplied at a depth of 5 cm whenever hairline cracks appeared in the soil. For the FWT treatment, irrigation was provided at a 5 cm depth once water levels had depleted to 15 cm. Under the IW/CPE method, an irrigation ratio of 0.8 was maintained from 21 DAS until panicle initiation, increasing to 1.0 from panicle initiation to harvest. The conventional practice of continuous flooding were from 21 DAS. This study focused on managing moisture stress through different irrigation methods and stress mitigation during the cropping season to achieve improved and sustainable yield. Drought mitigation in various plots was supported by the application of 1 % PPFM spray, 50 ppm paclobutrazol and soil incorporation of AM fungi at a rate of 100 g m⁻² during critical stages. A control plot was also maintained to evaluate the performance of DSR in comparison to the drought management treatments. Weed control measures involved the application of a pre-emergence herbicide, pretilachlor (0.75 kg ha⁻¹), at 8 DAS, followed by a post-emergence herbicide, bispyribac sodium (200 mL ha⁻¹), as per recommended guidelines. Once the crop reached physiological maturity, harvesting was carried out. The border rows were harvested first but were excluded from yield calculations.

Yield analysis

Grain yield from each net plot was measured after threshing, cleaning and drying, with a moisture content of 14 %. The final grain weight was expressed in t ha⁻¹. Straw yield was recorded after being sun-dried for three days and was also expressed in t ha⁻¹.

Nutrient analysis

The nutrient content in plant samples was analysed using standard procedures and expressed as a percentage (Table 1). Total nutrient uptake was determined by multiplying the nutrient content (%) by the dry matter yield of each treatment. The final uptake values were recorded in kg ha⁻¹ at the harvest stage.

Post-harvest soil available nutrients

The soil samples were collected after harvest from each plot, which aided in the analysis of available soil nitrogen (19), phosphorous (20) and potassium (21).

Economics

The gross returns, net returns and benefit-cost (B:C) ratio were calculated for all plots. The economic analysis considered expenses related to input procurement, labour costs and the prevailing market prices of the harvested produce. The formulas used to determine gross return, net return and the B:C ratio are provided below.

Gross income (₹ ha⁻¹) =

$$\text{Yield (t ha}^{-1}\text{)} \times \text{market value of produce (Eqn. 1)}$$

Table 1. Methods used for the determination of nutrient contents

Parameters	Methods	References
Nitrogen	Micro Kjeldahl method	(18)
Phosphorous	Triple acid digestion with calorimetric estimation	(21)
Potassium	Triple acid digestion with the flame photometric technique	(21)

Net income (\bar{r} ha⁻¹) = Gross income - Cost of cultivation (Eqn. 2)

$$\text{B:C ratio} = \frac{\text{Gross income}}{\text{Cost of cultivation}} \quad (\text{Eqn. 3})$$

Statistical analysis

The collected data were analysed statistically using AGRES software version 7.0. When treatment differences were found to be significant (S), critical differences (CD) were calculated at a 5% probability level. Non-significant treatment differences were indicated as NS.

Results

Grain yield

The study findings indicate that the highest grain yield of 6.7 t ha⁻¹ was recorded under the conventional continuous flooding method, which was statistically comparable to the AWD method with a yield of 6.3 t ha⁻¹ (Table 2). In contrast, irrigation based on the IW/CPE ratio resulted in the lowest grain yield of 4.3 t ha⁻¹. Among the various stress mitigation strategies, the highest grain yield of 6.3 t ha⁻¹ was achieved with the application of PPFM through 1% seed treatment combined with a 1% foliar spray at critical growth stages, which was statistically on par with seed treatment and soil application of AM fungi that produced 6.0 t ha⁻¹. The lowest grain yield (4.8 t ha⁻¹) was observed in the control plot. Regarding interaction effects, the combination of continuous flooding with PPFM application resulted in the highest grain yield of 7.6 t ha⁻¹, which was statistically similar to AWD combined with the same PPFM treatment, yielding 7.1 t ha⁻¹. Table 2 also shows that the lowest grain yield (3.4 t ha⁻¹) was recorded under irrigation based on the IW/CPE ratio in combination with the control treatment.

Straw yield

The results of the irrigation scheduling methods revealed that the highest straw yield was obtained under continuous flooding (7.3 t ha⁻¹), which was statistically similar to the AWD method, producing 7.1 t ha⁻¹ of straw (Table 2). In contrast, the lowest straw yield (4.9 t ha⁻¹) was recorded under irrigation based on the IW/CPE ratio. Among the different stress mitigation techniques, the highest straw yield (7.1 t ha⁻¹) was observed with the application of PPFM. The next best treatment was seed treatment and soil application of AM fungi, which produced a straw yield of 6.8 t ha⁻¹, a value statistically

comparable to the PPFM treatment. The control resulted in a significantly lower straw yield of 5.5 t ha⁻¹. Regarding the interaction between irrigation and stress mitigation strategies, the combination of continuous flooding with PPFM application (1% seed treatment + 1% foliar spray at critical stages) produced the highest straw yield of 8.3 t ha⁻¹ (Table 2). This was statistically on par with AWD with the same PPFM treatment, which yielded 8.0 t ha⁻¹. The lowest straw yield (3.8 t ha⁻¹) was recorded in the IW/CPE ratio treatment combined with the control.

Nitrogen uptake

The highest N uptake of 100.9 kg ha⁻¹ was recorded under continuous flooding, followed by AWD, which had a N uptake of 96.1 kg ha⁻¹ at harvest (Table 3). The lowest N uptake (67.8 kg ha⁻¹) was observed under irrigation based on the IW/CPE ratio. Among the different stress mitigation strategies, the application of PPFM through 1% seed treatment combined with a 1% foliar spray at critical stages resulted in the highest N uptake of 94.2 kg ha⁻¹ at harvest. Similarly, seed treatment and soil application of AM showed an N uptake of 92.7 kg ha⁻¹, which was statistically comparable to the PPFM treatment. The lowest N uptake (75.2 kg ha⁻¹) was recorded in the control treatment. Regarding the interaction between irrigation and stress management techniques, the highest N uptake (110.3 kg ha⁻¹) was found in continuous flooding combined with PPFM application. This was statistically similar to AWD with PPFM treatment, which resulted in an N uptake of 108.4 kg ha⁻¹ (Table 3). The lowest N uptake at harvest (57.3 kg ha⁻¹) was recorded under the IW/CPE ratio treatment combined with the control.

Phosphorous uptake

In terms of irrigation scheduling, continuous flooding resulted in the highest phosphorus (P) uptake at harvest, recording 30.3 kg ha⁻¹. However, the AWD showed a statistically similar P uptake of 29.2 kg ha⁻¹ (Table 3). The lowest P uptake of 22.9 kg ha⁻¹ was observed in the IW/CPE ratio treatment. Among the various stress mitigation strategies, seed treatment and soil application of AM fungi led to the highest P uptake of 32.8 kg ha⁻¹ at harvest. This was statistically comparable to the PPFM application at critical growth stages, which recorded a P uptake of 30.8 kg ha⁻¹. The lowest P uptake at harvest (18.0 kg ha⁻¹) was found in the control treatment. Regarding the interaction between irrigation methods and stress management practices, the highest P uptake at harvest (37.3 kg ha⁻¹) was recorded in continuous flooding combined with application of AM fungi. This was statistically on par with AWD irrigation combined with the AM

Table 2. Effect of irrigation scheduling and moisture stress mitigation techniques on grain yield and straw yield

	Grain yield (t ha ⁻¹)					Straw yield (t ha ⁻¹)					
	S ₁	S ₂	S ₃	S ₄	Mean	S ₁	S ₂	S ₃	S ₄	Mean	
M ₁	7.1	6.1	6.4	5.7	6.3	M ₁	8.0	6.9	7.4	6.1	7.1
M ₂	4.8	4.3	4.8	3.4	4.3	M ₂	5.4	5.3	5.3	3.8	4.9
M ₃	5.6	5.3	5.6	4.4	5.3	M ₃	6.9	6.1	6.5	5.5	6.3
M ₄	7.6	6.3	7.1	5.8	6.7	M ₄	8.3	6.3	8.0	6.5	7.3
Mean	6.3	5.5	6.0	4.8		Mean	7.1	6.2	6.8	5.5	
	M	S	M at S	S at M			M	S	M at S	S at M	
SEd	0.23	0.23	0.23	0.23		SEd	0.26	0.26	0.26	0.26	
CD (p= 0.05)	0.50	0.50	0.51	0.50		CD (p= 0.05)	0.55	0.56	0.56	0.57	

Table 3. Effect of irrigation scheduling and moisture stress mitigation techniques on plant N, P and K uptake

	N (kg ha ⁻¹)					P (kg ha ⁻¹)					K (kg ha ⁻¹)						
	S ₁	S ₂	S ₃	S ₄	Mean	S ₁	S ₂	S ₃	S ₄	Mean	S ₁	S ₂	S ₃	S ₄	Mean		
M ₁	108.4	90.3	99.4	86.3	96.1	M ₁	34.0	29.2	35.7	18.0	29.2	M ₁	123.8	113.0	116.0	80.0	108.2
M ₂	67.6	72.1	74.1	57.3	67.8	M ₂	24.8	23.8	26.1	16.8	22.9	M ₂	85.8	81.8	88.4	73.6	82.4
M ₃	90.4	82.5	88.9	68.9	82.7	M ₃	29.7	21.4	29.9	18.7	24.9	M ₃	96.9	85.4	96.2	88.7	91.8
M ₄	110.3	96.3	108.4	88.4	100.9	M ₄	34.6	31.0	37.3	18.4	30.3	M ₄	125.7	110.1	119.4	94.3	112.4
Mean	94.2	85.3	92.7	75.2		Mean	30.8	26.4	32.3	18.0		Mean	108.1	97.6	105.0	84.1	
	M	S	M at S	S at M			M	S	M at S	S at M			M	S	M at S	S at M	
SEd	2.00	1.86	2.08	1.98		SEd	0.78	0.73	1.06	1.02		SEd	3.21	3.46	3.57	3.39	
CD (p=0.05)	4.32	4.01	4.48	4.25		CD (p=0.05)	1.73	1.62	2.30	2.20		CD (p=0.05)	6.93	7.21	7.54	7.18	

fungi treatment, which resulted in a P uptake of 35.7 kg ha⁻¹ (Table 3). The lowest P uptake (16.8 kg ha⁻¹) was observed in the IW/CPE ratio treatment combined with the control.

Potassium uptake

Different irrigation methods significantly influenced potassium (K) uptake; continuous flooding resulted in the highest uptake of 112.4 kg ha⁻¹, which was statistically comparable to the AWD method with 108.2 kg ha⁻¹ at harvest (Table 3). The lowest K uptake (82.4 kg ha⁻¹) was recorded in the IW/CPE ratio treatment. Among stress mitigation strategies, the application of PPFM at critical stages led to the highest K uptake of 108.1 kg ha⁻¹. Soil application of AM fungi showed a comparable K uptake of 105.0 kg ha⁻¹. The control recorded the lowest uptake of 84.1 kg ha⁻¹. A significant interaction effect was observed between irrigation scheduling and stress mitigation practices in DSR. Table 3 showed that the highest K uptake of 125.7 kg ha⁻¹ at harvest was recorded in continuous flooding combined with PPFM application. This was statistically similar to the AWD with PPFM application, which recorded a K uptake of 123.8 kg ha⁻¹. The lowest uptake of 73.6 kg ha⁻¹ was noted in the IW/CPE ratio + control.

Post-harvest soil nutrient availability

Soil available nitrogen

Among the different irrigation scheduling methods, the IW/CPE ratio resulted in the highest soil N availability at harvest with a value of 192.6 kg ha⁻¹ (Table 4). This was statistically similar to irrigation at 15 cm water depletion using FWT, which recorded 183.0 kg ha⁻¹ of available soil N. In contrast, continuous flooding had the lowest soil N availability (141.6 kg ha⁻¹). Regarding stress mitigation strategies, the highest soil N availability at harvest (186.1 kg ha⁻¹) was observed with PPFM application at critical stages. A comparable result was noted for the application of AM fungi, which recorded 179.9 kg ha⁻¹. The lowest N availability of 149.2 kg ha⁻¹ was found in the control (Table 4). In terms of interaction effects, the highest soil N availability of 220.4 kg ha⁻¹ was recorded in the treatment irrigated using the IW/

CPE ratio with PPFM application (Table 4). This was followed by the IW/CPE ratio with application of AM fungi, which had an available soil N of 201.5 kg ha⁻¹. The lowest soil N availability (120.4 kg ha⁻¹) was observed in the continuous flooding treatment with the control.

Available phosphorus

The method of irrigation scheduling had a significant impact on soil P availability. As shown in Table 4, the highest soil P availability of 16.3 kg ha⁻¹ was recorded under irrigation based on the IW/CPE ratio, which was statistically comparable to the 15 cm water depletion treatment using a FWT, where P availability was 15.4 kg ha⁻¹. In contrast, continuous flooding resulted in the lowest soil P availability of 12.9 kg ha⁻¹. Among the different stress mitigation techniques, soil application of AM fungi led to the highest soil P availability of 17.2 kg ha⁻¹. This was followed by PPFM at critical stages, which recorded a P availability of 16.3 kg ha⁻¹ (Table 4). The lowest P availability in the soil (10.8 kg ha⁻¹) was observed in the control treatment (S₄). Both irrigation scheduling and stress mitigation techniques influenced soil P availability. The highest soil P availability of 18.2 kg ha⁻¹ was recorded in the IW/CPE ratio irrigation method with soil application of AM fungi. Conversely, the lowest soil P availability of 9.2 kg ha⁻¹ was found in the continuous flooding control treatment.

Potassium availability

Different irrigation scheduling methods significantly influenced soil K availability at the harvest stage of DSR. The highest soil K availability of 186.8 kg ha⁻¹ was observed under the IW/CPE ratio. This was statistically comparable to the irrigation treatment with 15 cm water depletion using an FWT, which recorded a soil K availability of 178.9 kg ha⁻¹. Table 4 shows that the continuous flooding resulted in the lowest soil K availability of 137.9 kg ha⁻¹. Regarding stress mitigation techniques, the application of PPFM recorded the highest soil K availability of 197.4 kg ha⁻¹. This was statistically similar to the soil application of AM fungi, which observed 187.7 kg ha⁻¹ of available potassium at harvest. The lowest available soil K of 120.2 kg ha⁻¹ was found in the control treatment. The interaction between irrigation

Table 4. Effect of irrigation scheduling and moisture stress mitigation techniques on available soil NPK at harvest

	N (kg ha ⁻¹)					P (kg ha ⁻¹)					K (kg ha ⁻¹)						
	S ₁	S ₂	S ₃	S ₄	Mean	S ₁	S ₂	S ₃	S ₄	Mean	S ₁	S ₂	S ₃	S ₄	Mean		
M ₁	173.5	157.4	172.4	156.4	164.9	M ₁	15.9	13.8	17.8	9.8	14.3	M ₁	184.7	153.9	173.7	114.8	156.8
M ₂	220.4	186.3	210.5	153.1	192.6	M ₂	17.6	16.7	18.2	12.6	16.3	M ₂	227.2	167.1	220.3	132.6	186.8
M ₃	198.3	178.2	188.8	166.8	183.0	M ₃	17.2	15.3	17.5	11.6	15.4	M ₃	211.8	156.8	218.5	128.6	178.9
M ₄	152.3	145.7	147.9	120.4	141.6	M ₄	14.3	12.8	15.3	9.2	12.9	M ₄	165.8	142.7	138.3	104.8	137.9
Mean	186.1	166.9	179.9	149.2		Mean	16.3	14.7	17.2	10.8		Mean	197.4	155.1	187.7	120.2	
	M	S	M at S	S at M			M	S	M at S	S at M			M	S	M at S	S at M	
SEd	5.0	5.0	5.2	5.1		SEd	0.44	0.42	0.45	0.47		SEd	5.6	5.3	6.2	5.9	
CD (p=0.05)	10.8	10.9	11.1	11.0		CD (p=0.05)	0.94	0.90	1.0	1.0		CD (p=0.05)	12.1	11.4	13.3	12.8	

Table 5. Effect of irrigation scheduling and moisture stress mitigation techniques on profitability

Treatment	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B:C ratio
M ₁ S ₁	124684	82832	2.98
M ₁ S ₂	111367	69830	2.68
M ₁ S ₃	116488	74814	2.80
M ₁ S ₄	92665	51489	2.25
M ₂ S ₁	98472	57694	2.41
M ₂ S ₂	90365	49809	2.23
M ₂ S ₃	96780	56133	2.38
M ₂ S ₄	80224	41804	2.09
M ₃ S ₁	100265	59208	2.44
M ₃ S ₂	92468	51706	2.27
M ₃ S ₃	97610	56680	2.38
M ₃ S ₄	84710	44925	2.13
M ₄ S ₁	130436	87950	3.07
M ₄ S ₂	114786	72802	2.73
M ₄ S ₃	119248	76892	2.82
M ₄ S ₄	95782	54001	2.29

methods and stress mitigation strategies also influenced soil K availability. The highest available soil K at harvest (227.2 kg ha⁻¹) was recorded in the IW/CPE ratio irrigation with PPFM application. This was statistically comparable to the IW/CPE ratio irrigation with soil application of AM fungi, which had an available soil K of 220.3 kg ha⁻¹. Conversely, the lowest soil K availability (104.8 kg ha⁻¹) was recorded in the continuous flooding with the control.

Profitability

Table 5 revealed that the irrigation scheduling and water stress mitigation methods show a significant difference in profitability. The highest gross return was recorded under continuous flooding with PPFM application at critical growth stages, generated ₹130436 ha⁻¹. This was statistically similar to the AWD with PPFM application, which yielded a gross return of ₹124684 ha⁻¹. In contrast, the lowest gross return of ₹80224 ha⁻¹ was observed under the IW/CPE ratio irrigation method with the control treatment. The maximum net return of ₹87950 ha⁻¹ was also achieved in the continuous flooding system combined with PPFM application, followed closely by AWD with the same PPFM application, which generated ₹82832 ha⁻¹ in net returns. The lowest net return was recorded in the IW/CPE ratio with the control treatment, accounting for ₹41804 ha⁻¹. Regarding the benefit-cost (B:C) ratio, the highest value of 3.07 was observed in continuous flooding combined with PPFM application. This was comparable to the AWD method with PPFM application, which had a B:C ratio of 2.98. The lowest B:C ratio of 2.09 was noted under the IW/CPE ratio with the control treatment.

Discussion

Yield

Crop yield serves as a crucial measure of productivity, influenced by various agronomic, environmental and management factors. This study examined yield performance under different treatments to evaluate the effects of irrigation and water stress management strategies. Continuous flooding resulted in the highest grain and straw yield, which was statistically comparable to the AWD irrigation method. These methods produced 35.1 % and 31.8 % higher grain yield and 30.6 % and 29.7 % higher straw yield, respectively, compared to the IW/CPE ratio irrigation method. The increased yield under continuous flooding and AWD could be attributed to improved spikelet m⁻¹, a higher percentage of filled grains and greater 1000-grain weight. These factors, along with better root

development and enhanced nutrient (NPK) absorption, contributed to overall plant growth, ultimately leading to improved yield (23). Adequate water and nutrient supply facilitated optimal plant growth, enhancing yield-related attributes such as the number of filled grains and grain weight (24). The increased straw yield may be linked to a higher number of tillers per unit area (25). Conversely, the lowest grain and straw yield were observed under the IW/CPE ratio method, likely due to water deficit-induced senescence, which negatively impacted grain filling, like chaffy grains and test weight, resulting in lower yield (26).

Regarding stress mitigation techniques, the highest grain and straw yield was recorded with the application of PPFM. The enhanced yield could be attributed to the role of Methylootrophs in increasing the polysaccharide fraction of the cell wall, which, in the presence of adequate soil moisture, contributed to better growth and yield attributes (27). Among the interaction effects, the combination of continuous flooding and PPFM application resulted in the highest grain and straw yield, which was statistically comparable to AWD with PPFM application. The improved yield in these treatments can be linked to enhanced plant growth due to sufficient moisture and nutrient availability, which facilitated better translocation of nutrients and increased photosynthetic efficiency (28). In contrast, the lowest grain and straw yield was recorded under the IW/CPE ratio combined with the control treatment due to limited moisture availability, which led to poor plant growth and reduced yield parameters, ultimately affecting both economic and biological yield (29).

Nutrient uptake

Nutrient uptake plays a crucial role in crop productivity as it directly influences biomass production and nutrient accumulation. In this study, nutrient uptake was assessed at the harvest stage. Among the irrigation treatments, continuous flooding resulted in the highest N, P and K uptake. This can be attributed to the availability of adequate water, which creates a favourable lowland environment for nutrient absorption, enhancing biomass accumulation and nutrient assimilation (30). Similarly, the AWD method showed comparable nutrient uptake to continuous flooding. This could be due to improved root development and better oxygen availability, which enhances nutrient absorption under intermittent irrigation (31). Furthermore, AWD supports microbial activity and aeration, facilitating nutrient transformation (32). In contrast, irrigation based on the IW/CPE ratio exhibited the lowest N, P and K uptake. The

limited soil moisture in this treatment likely restricted root growth and reduced nitrogen diffusion and transformation, negatively affecting nutrient uptake (33).

Regarding stress management strategies, the highest N and K uptake was recorded with the application of PPFM, which was statistically similar to the soil application of AM fungi. This could be due to enhanced carbohydrate allocation to roots under optimal conditions, reducing nitrogen dilution in grains and improving nutrient absorption (34). Meanwhile, the highest P uptake was observed in the soil application of AM fungi due to improved phosphorus mineralisation and translocation from the soil to plant shoots under favourable conditions (35). The interaction between irrigation and stress mitigation methods showed that continuous flooding combined with PPFM application led to the highest N and K uptake at harvest. This could be attributed to increased urease activity in paddy soil, which enhances nitrogen metabolism, leading to higher nutrient concentrations in leaves. Additionally, previous studies have shown that Methylophobus stimulate indole acetic acid (IAA) production, promoting root growth and nitrogen uptake under flooded conditions (36, 37). Similarly, AWD combined with PPFM application resulted in comparable N and K uptake, which may be due to improved root volume and moisture availability (38). The lowest nutrient uptake was recorded in the IW/CPE ratio method combined with the control treatment. This could be due to reduced shoot growth and root development caused by water deficit. However, continuous flooding with soil application of AM fungi exhibited the highest P uptake. This was likely due to adequate soil moisture, which improved phosphorus absorption, uptake and translocation to plant shoots and other rice plant components (39).

Soil available nutrients

The availability of soil N, P and K after harvest is significantly influenced by irrigation scheduling and drought management strategies. Table 4 revealed that the highest levels of available NPK were observed under the IW/CPE ratio irrigation method. This increased nutrient availability could be due to lower soil moisture levels, which may have restricted plant uptake of both applied and naturally present nutrients, resulting in higher residual nutrient content in the soil. In contrast, continuous flooding led to the lowest levels of available NPK, likely because excessive moisture interfered with nutrient absorption and mineralisation (40). Regarding phosphorus availability, the highest levels were found in the treatment involving soil application of AM fungi. This could be attributed to the fungi's ability to produce extracellular phosphate enzymes and organic acids, which enhance phosphorus solubilization and increase its availability in the soil. In terms of interaction effects, the combination of the IW/CPE ratio irrigation method with the control treatment resulted in the highest residual NPK levels. This outcome is due to reduced nutrient uptake under unfavourable moisture conditions, leaving more nutrients unutilized in the soil after harvest (41).

Profitability

Profitability plays a crucial role in determining the economic viability of agricultural practices. In this study, key financial indicators such as gross returns, net returns and the benefit-cost ratio were evaluated under different treatments. The continuous flooding system, PPFM application recorded the highest economic returns, with a gross return of ₹130436 ha⁻¹, net return of ₹87950 ha⁻¹ and a B:C ratio of 3.07. Similarly, the AWD method, coupled with PPFM application,

resulted in comparable outcomes, recording a gross return of ₹124684 ha⁻¹, net return of ₹82832 ha⁻¹ and a B:C ratio of 2.98. The higher profitability of these treatments can be attributed to increased yield potential, efficient water utilisation and reduced labour and irrigation time, which contributed to greater economic benefits compared to the control (42). On the other hand, the irrigation method based on the IW/CPE ratio combined with the control treatment recorded the lowest gross return, net return and B:C ratio. This reduction in profitability was likely due to water scarcity during critical growth stages, leading to lower grain yield and consequently, reduced economic returns (43).

Conclusion

The study revealed a significant variation in rice grain and straw yields, nutrient uptake and post-harvest soil nutrient availability due to different irrigation scheduling methods and stress mitigation strategies. Among the irrigation methods, continuous flooding consistently resulted in the highest yields, followed closely by AWD. The application of PPFM through 1% seed treatment and 1% foliar spray at critical stages significantly enhanced both yield and nutrient absorption across all treatments. Regarding post-harvest soil nutrient availability, irrigation based on the IW/CPE ratio led to the highest soil nitrogen, phosphorus and potassium levels, particularly when combined with AM fungi (S₃). However, nutrient uptake was maximised under continuous flooding and AWD, especially with PPFM application. In terms of economic viability, continuous flooding with PPFM application resulted in the highest net returns and B:C ratio, followed by AWD with PPFM application. Thus, this study confirms that AWD, when integrated with the PPFM application, is the optimal strategy for maximising rice yield, nutrient uptake and profitability. Therefore, adopting DSR offers significant socio-economic benefits, including reduced labour costs, lower input expenses and higher profitability, making it a sustainable alternative to traditional rice cultivation. Its role in water conservation, reduced greenhouse gas emissions and improved farm efficiency enhances long-term agricultural resilience.

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Authors' contributions

AN carried out the field experiment, data analysis and prepared the manuscript. JM guided experimentation, corrected the manuscript and provided assistance. RKD provided the necessary machinery and guidance for experimenting. HM made corrections to the manuscript. All authors read and approved the final manuscript.

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

During the preparation of the manuscript, the first author used the ChatGPT AI tool only to improve the language and readability of the manuscript in the introduction and conclusion. After using this tool, the corresponding author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

References

- Sen S, Chakraborty R, Kalita P. Rice-not just a staple food: A comprehensive review on its phytochemicals and therapeutic potential. *Trends Food Sci Technol.* 2020;97:265-85. <https://doi.org/10.1016/j.tifs.2020.01.022>
- Muthayya S, Sugimoto JD, Montgomery S, Maberly GF. An overview of global rice production, supply, trade, and consumption. *Ann N Y Acad Sci.* 2014;1324(1):7-14. <https://doi.org/10.1111/nyas.12540>
- Bandumula N. Rice production in Asia: Key to global food security. *Proc Natl Acad Sci India Sect B Biol Sci.* 2018;88:1323-8. <https://doi.org/10.1007/s40011-017-0867-7>
- Pathak H, Tewari AN, Sankhyan S, Dubey DS, Mina U, Singh VK, et al. Direct-seeded rice: potential, performance and problems-A review. *Curr Adv Agric Sci.* 2011;3(2):77-88.
- Kaur J, Singh A. Direct seeded rice: Prospects, problems/constraints and researchable issues in India. *Curr Agric Res J.* 2017;5(1):13. <https://doi.org/10.12944/CARJ.5.1.03>
- Farooq M, Wahid A, Lee DJ, Cheema SA, Aziz T. Drought stress: comparative time course action of the foliar applied glycinebetaine, salicylic acid, nitrous oxide, brassinosteroids and spermine in improving drought resistance of rice. *J Agron Crop Sci.* 2010;196(5):336-45. <https://doi.org/10.1111/j.1439-037X.2010.00422.x>
- Kumar V, Ladha JK. Direct seeding of rice: recent developments and future research needs. *Adv Agron.* 2011;111:297-413. <https://doi.org/10.1016/B978-0-12-387689-8.00001-1>
- Bhatt R, Oliveira MW, Verma KK, Garg AK, Kaur G, Laing AM, et al. Challenges, scope, and upcoming strategies for direct seeding of rice: a global meta-analysis. *Agric Mech Asia Afr Lat Am.* 2023;54(4):12825-63.
- Chauhan BS, Ahmed S, Awan TH, Jabran K, Manalil S. Integrated weed management approach to improve weed control efficiencies for sustainable rice production in dry-seeded systems. *Crop Prot.* 2015;71:19-24. <https://doi.org/10.1016/j.cropro.2015.01.012>
- Jalindar MK, Praveen Rao V, Ramulu V, Avil Kumar K, Uma Devi M. Effectiveness of field water tube for standardization of alternate wetting and drying (AWD) method of water management in lowland rice (*Oryza sativa* L.). *Irrig Drain.* 2019;68(4):679-89. <https://doi.org/10.1002/ird.2354>
- Kumar S, Singh RS, Yadav L, Kumar K. Effect of moisture regime and integrated nutrient supply on growth, yield and economics of transplanted rice. *Oryza.* 2013;50(2):189-91.
- Singh VP, Dhyani VC, Singh SP, Kumar A, Manalil S, Chauhan BS. Effect of herbicides on weed management in dry-seeded rice sown under different tillage systems. *Crop Prot.* 2016;80:118-26. <https://doi.org/10.1016/j.cropro.2015.09.018>
- Bouman BA, Humphreys E, Tuong TP, Barker R. Rice and water. *Adv Agron.* 2007;92:187-237. [https://doi.org/10.1016/S0065-2113\(04\)92004-4](https://doi.org/10.1016/S0065-2113(04)92004-4)
- Sander BO, Wassmann R, Siopongco JD. Mitigating greenhouse gas emissions from rice production through water-saving techniques: potential, adoption and empirical evidence. In: *Climate change and agricultural water management in developing countries.* 2016. p. 193-207. <https://doi.org/10.1079/9781780643663.0193>
- Belder P, Bouman BA, Cabangon R, Guoan L, Quilang EJ, Yuanhua L, et al. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agric Water Manag.* 2004;65(3):193-210. <https://doi.org/10.1016/j.agwat.2003.09.002>
- Rao AN, Johnson DE, Sivaprasad B, Ladha JK, Mortimer AM. Weed management in direct-seeded rice. *Adv Agron.* 2007;93:153-255. [https://doi.org/10.1016/S0065-2113\(06\)93004-1](https://doi.org/10.1016/S0065-2113(06)93004-1)
- Chakraborty T, Akhtar N. Biofertilizers: Characteristic features and applications. In: *Biofertilizers: Study and Impact.* 2021;20:429-89. <https://doi.org/10.1002/9781119724995.ch15>
- Humphries EC. Mineral composition and ash analysis. In: Peach K, Tracey MV, editors. *Modern Methods of Plant Analysis.* Berlin: Springer-Verlag. 1956;1:468-502. https://doi.org/10.1007/978-3-662-25300-7_17
- Subbiah BV, Asija GL. A rapid procedure for determination of available nitrogen in soil. *Curr Sci.* 1956;25:259-60.
- Olsen S, Cole C, Watanabe F. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular.* 1954;939:1-43.
- Jackson M. *Soil chemical analysis.* New Delhi: Prentice Hall of India Pvt. Ltd.; 1973;498:38-336.
- Gomez KA, Gomez AA. *Statistical Procedures for Agricultural Research.* 2nd ed. New Delhi, India: Wiley India Pvt Ltd; 2010.
- Senthilkumar K, Bindraban PS, Thiyagarajan TM, De Ridder N, Giller KE. Modified rice cultivation in Tamil Nadu, India: yield gains and farmers' (lack of) acceptance. *Agric Syst.* 2008;98(2):82-94. <https://doi.org/10.1016/j.agsy.2008.04.002>
- Oliver MM, Talukder MS, Ahmed M. Alternate wetting and drying irrigation for rice cultivation. *J Bangladesh Agric Univ.* 2008;6(2). <https://doi.org/10.3329/jbau.v6i2.4841>
- Thakur AK, Mohanty RK, Patil DU, Kumar A. Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice. *Paddy Water Environ.* 2014;12(4):413-24. <https://doi.org/10.1007/s10333-013-0397-8>
- Yang J, Zhou Q, Zhang J. Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. *Crop J.* 2017;5(2):151-8. <https://doi.org/10.1016/j.cj.2016.06.002>
- Yurimoto H, Iguchi H, Di Thien DT, Tani A, Okumoto Y, Ota A, et al. Methanol bioeconomy: promotion of rice crop yield in paddy fields with microbial cells prepared from natural gas-derived C1 compound. *Microb Biotechnol.* 2021;14(4):1385-96. <https://doi.org/10.1111/1751-7915.13725>
- Dari B, Sihi D, Bal SK, Kunwar S. Performance of direct-seeded rice under various dates of sowing and irrigation regimes in semi-arid region of India. *Paddy Water Environ.* 2017;15:395-401. <https://doi.org/10.1007/s10333-016-0557-8>
- Elanchezian R, Haris AA, Kumar S, Singh SS. Positive impact of paclobutrazol on gas exchange, chlorophyll fluorescence and yield parameters under submergence stress in rice. *Indian J Plant Physiol.* 2015;20:111-15. <https://doi.org/10.1007/s40502-015-0144-9>
- Chaudhury J, Mandal UK, Sharma KL, Ghosh H, Mandal B. Assessing soil quality under long-term rice-based cropping system. *Commun Soil Sci Plant Anal.* 2005;36(9-10):1141-61. <https://doi.org/10.1081/CSS-200056885>
- Solaiman MZ, Hirata H. Effects of indigenous arbuscular mycorrhizal fungi in paddy fields on rice growth and N, P, K nutrition under different water regimes. *Soil Sci Plant Nutr.* 1995;41(3):505-14. <https://doi.org/10.1080/00380768.1995.10419612>
- Yang C, Yang L, Yang Y, Ouyang Z. Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. *Agric Water Manag.* 2004;70(1):67-

81. <https://doi.org/10.1016/j.agwat.2004.05.003>
33. Dong NM, Brandt KK, Sørensen J, Hung NN, Van Hach C, Tan PS, et al. Effects of alternating wetting and drying versus continuous flooding on fertilizer nitrogen fate in rice fields in the Mekong Delta, Vietnam. *Soil Biol Biochem.* 2012;47:166–74. <https://doi.org/10.1016/j.soilbio.2011.12.028>
34. Panneerselvam P, Kumar U, Sugitha TC, Parameswaran C, Sahoo S, Binodh AK, et al. Arbuscular mycorrhizal fungi (AMF) for sustainable rice production. In: *Advances in Soil Microbiology: Recent Trends and Future Prospects. Vol. 2: Soil–Microbe–Plant Interaction.* Singapore: Springer; 2017. p. 99–126. https://doi.org/10.1007/978-981-10-7380-9_6
35. Madhaiyan M, Poonguzhali S, Senthilkumar M, Seshadri S, Chung H, Jinchul YA, et al. Growth promotion and induction of systemic resistance in rice cultivar Co-47 (*Oryza sativa* L.) by *Methylobacterium* spp. *Bot Bull Acad Sin.* 2004;1:45.
36. Kumar A, Mahapatra BS, Singh VP, Shukla A, Negi MS, Yadav A, et al. Effect of nutrient levels on yield, nutrient uptake and economics of Indian mustard (*Brassica juncea*) in tarai region of Uttarakhand. *Indian J Agron.* 2017;62(3):378–81. <https://doi.org/10.59797/ija.v62i3.4313>
37. Lee HS, Madhaiyan M, Kim CW, Choi SJ, Chung KY, Sa TM. Physiological enhancement of early growth of rice seedlings (*Oryza sativa* L.) by production of phytohormone of N₂-fixing methylotrophic isolates. *Biol Fertil Soils.* 2006;42:402–8. <https://doi.org/10.1007/s00374-006-0083-8>
38. Sridevi V, Chellamuthu V. Influence of system of rice intensification on growth, yield and nutrient uptake of rice (*Oryza sativa* L.). *Madras Agric J.* 2012;99:27–99.
39. Sharma P, Singh G, Singh RP. Conservation tillage, optimal water and organic nutrient supply enhance soil microbial activities during wheat (*Triticum aestivum* L.) cultivation. *Braz J Microbiol.* 2011;42:531–42. <https://doi.org/10.1590/S1517-83822011000200018>
40. Chowdhury MR, Kumar V, Sattar A, Brahmachari K. Studies on the water use efficiency and nutrient uptake by rice under system of intensification. *Bioscan.* 2014;9(1):85–8.
41. Okonji CJ, Sakariyawo OS, Okeleye KA, Osunbiyi AG, Ajayi EO. Effects of arbuscular mycorrhizal fungal inoculation on soil properties and yield of selected rice varieties. *J Agric Sci (Belgr).* 2018;63(2):153–70. <https://doi.org/10.2298/JAS1802153O>
42. Nalley L, Linquist B, Kovacs K, Anders M. The economic viability of alternative wetting and drying irrigation in Arkansas rice production. *Agron J.* 2015;107(2):579–87. <https://doi.org/10.2134/agronj14.0468>
43. Lampayan RM, Rejesus RM, Singleton GR, Bouman BA. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Res.* 2015;170:95–108. <https://doi.org/10.1016/j.fcr.2014.10.013>

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