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EFFECTS OF IRRIGATION AND NUTRIENT MANAGEMENT PRACTICES ON PHYSIOLOGICAL AND YIELD ATTRIBUTES IN RICE

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ABSTRACT

Intense rice irrigation poses a threat to global water security due to high demand from non-agricultural sectors, especially under climate change and associated rainfall vagaries. This necessitates reduced irrigation options with limited yield and stress impact. This trial has focused on finding irrigation alternatives with different soil amendments and nutrient management practices to minimize water stress and achieve higher yield in rice. A two-year field study was conducted to explore the effects of six soil amendments and nutrient management options under two irrigation regimes on physiological characteristics, yield, and water productivity of rice. The results indicated that alternate wetting and drying 15 cm (AWD_{15}) resulted in higher photosynthetic pigments, viz. total chlorophyll and carotenoids, over the continuous flooding regime (CF). AWD irrigation did not cause notable cell damage and maintained higher relative water content and lower malondialdehyde (MDA) activity. The higher water productivity (WP), panicle density, and yield of rice under AWD over the CF regime indicated that this transformative agricultural practice has immense potential in the regulation of water against climate change. The result implies that AWD can be safely substituted for the CF regime in rice to conserve water resources with negligible impact on yield.

***Key words*:** Alternate wetting and drying; Conservative irrigation; Rice; Rice physiology; Water productivity

Introduction

Rice is usually regarded as a water-intensive crop because of its larger water footprint, which is the volume of water required to produce 1 kg of paddy. Among the three largest rice producers in the world, Bangladesh has a higher water footprint of 2100-3300 L/kg, followed by India (1500-2000 L/kg) and China (1300 L/kg), with a global share of about 60% in rice production (Hanasaki *et al*., 2010; USDA, 2025; Debnath *et al*., 2025). As the demand for water from the domestic, industrial, and environmental sectors grows, alternative irrigation practices, particularly in rice cultivation, must be implemented to efficiently use applied water and maximise agricultural production (Mallareddy *et al*., 2023; Frontuto *et al*., 2025). Apart from rising competition for water, the prevalence of climate change and resultant scanty rainfall, coupled with high temperatures have aggravated the deficiency of water, and it's high time to shift from water-intensive rice to optimum water rice culture.

Alternate wetting and drying (AWD) is considered a conservative irrigation practice, which saves water to the tune of 20-30% compared to continuous flooded irrigation without significant yield reduction in rice (Carrijo *et al*., 2017). Implementing AWD irrigation in rice may cause mild water stress to the crop and may have an impact on rice growth and development, particularly physiological characteristics such as relative water content, plant pigments, and malondialdehyde (MDA) in the crop, owing to its shallow-rooted characteristics, and it depends on the period of unsaturated soil conditions

(Hazman *et al*., 2023; Liu *et al*., 2023; Wichaidist *et al*., 2025a). Soil dryness on controlled irrigation practices and associated stress could be managed by supplementing the soil with materials like biochar that holds moisture in the soil, which helps to improve nutrient use efficiency under limited water supply, and growth of crops can be improved as in flooded irrigation (Haque *et al*., 2021; Kang *et al*., 2022). Furthermore, nutrient management strategies play a role in stress mitigation and maintaining a favorable water balance, physiological activities, and crop production (Guo *et al*., 2008). It has become imperative to address the issue of water management and climate change to optimize production in rice systems. The aim was to develop nutrient management/soil amendment options for a profitable conservative irrigation rice system to mitigate mild water stress on limited water supply and associated changes in physiological characteristics in rice.

Materials and Methods

Study area

The study investigated the effect of soil amendments and nutrient efficient management schedule under water saving management practices on the physiological development, yield and water use efficiency in terms of water productivity in rice during rabi seasons of 2024 and 2025 at Agricultural Research Station, Mannuthy, Kerala Agricultural University, Thrissur, India, with latitude of 10.535913^0 N, longitude of 76.267089^0 E, and at an altitude of 20 m above sea level. The experimental site enjoys a typical humid tropical climate with annual average rainfall of 300 cm, receives 75% of rainfall during the south west monsoon (June-September) and 15% during the north east monsoon (October-December).

Experimental design and treatments

The field trial was laid out in a factorial randomized complete block design (RCBD) with two factors replicated thrice. Each plot covered an area of 24 m^2. The variety Uma, a medium-duration variety, was used for the experiment. The nursery was prepared by sowing 48-hour pre-soaked and incubated germinated seeds @ 80 kg/ha in shallow plastic trays filled with soil. Trays were arranged in a levelled and drained area and were irrigated regularly, and 25-day-old seedlings were transplanted in plots at a spacing of 20 × 10 cm.

Two irrigation regimes were implemented as factor A: AWD_{15cm} and CF irrigation. The water level was maintained at 5 cm above ground level in all the plots irrespective of irrigation regimes up to 20 days after transplanting (DAT). The AWD irrigation regimes were imposed from 20 DAT by flooding to a depth of 5 cm above ground and allowed to drain 15 cm below ground, which then re-flooded to 5 cm above ground. The water level in the AWD plots was measured with the help of a field water pipe with a scalar measurement by which the water level can be measured. The depth of water was maintained at 5 cm one week before and after flowering in all the treatment plots, irrespective of AWD and CF. This cycle of AWD was followed till 2 weeks before harvest of the crop, except during the flowering stage. In the CF plots, the water level was maintained at 5 cm above ground level throughout the crop growth stages till 2 weeks before harvest. The plots were drained in both irrigation regimes during fertilizer application.

Six nutrient management techniques were implemented as factor B; S_1: recommended dose of fertilizer (RDF) of 90:45:45 kg/ha of N, P and K + recommended dose of nitrogen (RDN) through diammonium phosphate (DAP) and urea, S_2: RDF 90:45:45 kg/ha of N, P and K + RDN through ammonium phosphate sulphate (APS) and ammonium sulphate, S_3: RDF 90:45:45 kg/ha of N, P and K + RDN through APS and urea, S_4: RDF 90:45:45 kg/ha of N, P and K + RDN through APS and urea + phosphogypsum @ 56 kg/ha, S_5: RDF 90:45:45 kg/ha of N, P and K + RDN through APS and urea + lime 450 kg/ha + phosphogypsum @ 150 kg/ha, S_6: RDF 90:45:45 kg/ha of N, P and K + RDN through APS and urea + biochar @ 2 t/ha.

Liming was done @ 600 kg/ha in all the treatments in two splits, one at the time of ploughing (350 kg/ha) and the second one month after transplanting (250 kg/ha), except S_5. In S_5, lime and phosphogypsum in a 3:1 ratio was applied (lime @ 450 kg/ha + phosphogypsum @ 150 kg/ha). In treatment S_4, phosphogypsum @ 56 kg/ha was applied basally along with lime application. Lime and phosphogypsum were combined applied one week before transplanting. Recommended dose of fertilizer @ 90:45:45 kg/ha of N, P, and K was followed in all treatments in 3 splits as basal one day after transplanting (N50%, P100%, K50%), at active tillering (N25%), and at panicle initiation (N25%, K50%). Biochar @ 2 t/ha was applied in the S_6 treatment 2 days before transplanting. Harvesting was done at maturity, 135 days in year 1 and 131 days in year 2. All the other operations were done as per the package of practices of KAU (KAU, 2024).

Physiological parameters

Photosynthetic pigments:

Photosynthetic pigments such as chlorophyll and carotenoids were determined from fully expanded, mature and healthy leaves (third leaf from the top), cutting 0.05 g leaf sample into small pieces, extracted on dark store

for a period of 24 h with 10 ml of dimethyl sulfoxide (DMSO), the absorbance were taken using spectrophotometer at 480, 510, 645, and 663 nm (Hiscox and Israelstam, 1979). Total chlorophyll and carotenoid content were derived using the formula.

$$\text{Total chlorophyll (mg g}^{-1}) = (20.2\ A_{645} + 8.02\ A_{663}) \times \frac{V}{1000W}$$

$$\text{Carotenoid (mg g}^{-1}) = (7.6\ A_{480}) - (1.49\ A_{510}) \times \frac{V}{1000W}$$

Where,

A480 = absorbance at 480 nm;

A510 = absorbance at 510 nm;

A645 = absorbance at 645 nm;

A663 = absorbance at 663 nm;

W = fresh weight (g);

V = volume of DMSO (ml)

MDA content:

MDA content in leaves was determined by the thiobarbituric acid test (Heath and Packer, 1968). Leaf samples of 0.25 g were homogenized in 5 ml of 0.1% trichloroacetic acid (TCA) solution. The homogenate was then centrifuged at 1000 rpm for 5 min, and 1 ml of the supernatant was added to 4 ml of 20% TCA containing 0.5% thiobarbituric acid (TBA). The mixture was then incubated at 95^0c for 30 min and then placed in an ice bath to stop the reaction. The samples were then again centrifuged at 10000 rpm for 10 min, and the supernatant absorbance was then read in a spectrophotometer at 532 and 600 nm. MDA was calculated using the formula.

$$\text{MDA (micro-mol g}^{-1}) = \frac{(A_{532}-A_{600}) \times V_f \times V_e)}{(155 \times W \times V_a)}$$

Where,

A532 = absorbance at 532 nm;

A600 = absorbance at 600 nm;

V_f = final volume (ml);

V_e = volume of TCA used for extraction (ml);

155 = extinction coefficient;

W = fresh weight (g);

V_a = volume of plant sample solution (ml)

Relative water content:

Relative water content (RWC) was determined by the leaf turgid weight method suggested by Barrs and Weatherley (1962). The third leaf from the top was selected and made into 50 uniform leaf discs, then recorded its fresh weight (Fw). Leaf discs were then floated in water for 4 h to attain full turgidity, then the leaf discs were taken out, and the water droplets sticking on the leaf surface were removed using blotting sheets, and recorded the turgid weight (Tw). Leaf discs were then transferred to butter paper and kept in a hot air oven for 48 h at 80^0c, and after that, recorded the dry weight (Dw). RWC was calculated from the following formula.

$$\text{RWC (\%)} = \frac{\text{Fw-Dw}}{\text{Tw-Dw}} \times 100$$

Where,

Fw = fresh weight of leaf discs;

Dw = dry weight of leaf discs;

Tw = turgid weight of leaf discs

Water productivity:

Water productivity (WP) was determined by the method suggested by Molden *et al*. (1998), it is the ratio of the output (kg) derived from the system to the volume of water consumed (m^{-3}). WP was calculated using the following formula

$$\text{WP (kg m}^{-3}) = \frac{\text{Yield (kg/ha)}}{\text{Water consumed (m}^3\ \text{ha}^{-1})}$$

Yield parameters

Panicle density:

Panicle density, a primary yield component to estimate the crop yield was determined with the formula and the data is presented as panicles per square metre.

Panicles m^{-2} = (Number of hills m^{-2}) × (Average number of panicles per hill)

Filled grain ratio:

Filled grain ratio is vital to crop yield assessment as it measures the proportion of properly developed, healthy spikelets to the total number of spikelets produced by the plant. It was calculated using the formula.

$$\text{Filled grain ratio (\%)} = \frac{\text{Number of filled spikelets}}{\text{Total number of spikelets}} \times 100$$

Rice grain yield:

Grain yield was estimated at physiological maturity from a 10 m^2 area in each treatment plot. Grain yield (kg ha^{-1}) is reported at 14% moisture content.

Statistical analysis

The treatment effects were statistically analysed using the factorial randomized complete block design (RCBD) with the online statistical analysis software RAISINS (Hisham *et al*., 2025). The means were compared using analysis of variance (ANOVA) and Duncan's multiple

Table 1: Effect of irrigation regimes and nutrient management factors on total chlorophyll and carotenoid content.

	Total chlorophyll content (mg g^{-1} FW)							Carotenoid content (mg g^{-1} FW)						
Year 1														
Treatments	S_1	S_2	S_3	S_4	S_5	S_6	Mean	S_1	S_2	S_3	S_4	S_5	S_6	Mean
AWD_{15cm}	1.42 ^{a}	1.13^{b}	1.19^{ab}	1.31^{ab}	1.22^{ab}	1.21^{ab}	1.25	0.64^{a}	0.52^{bc}	0.56^{ab}	0.64^{a}	0.60^{ab}	0.55^{ab}	0.59
CF	0.84^{c}	1.25^{ab}	1.19^{ab}	1.37^{ab}	1.32^{ab}	1.23^{ab}	1.20	0.42^{c}	0.61^{ab}	0.59^{ab}	0.64^{a}	0.62^{ab}	0.59^{ab}	0.58
Mean	1.13	1.19	1.19	1.34	1.27	1.22		0.53	0.56	0.58	0.64	0.61	0.57	
Year 2														
AWD_{15cm}	2.96	3.00	2.39	2.56	2.74	2.31	2.66	1.17	1.10	0.89	0.91	1.01	0.85	0.99
CF	2.53	2.40	2.76	2.46	3.01	2.33	2.58	0.99	0.92	0.97	0.82	1.03	0.86	0.93
Mean	2.74	2.70	2.58	2.51	2.88	2.32		1.08	1.01	0.93	0.86	1.02	0.86	
Pooled data														
AWD_{15cm}	2.19^{a}	2.07^{ab}	1.79^{bc}	1.93^{ab}	1.98^{ab}	1.76^{bc}	1.95	2.19^{a}	2.07^{ab}	1.79^{bc}	1.93^{ab}	1.98^{ab}	1.76^{bc}	0.79
CF	1.68^{c}	1.82^{abc}	1.98^{ab}	1.92^{ab}	2.16^{ab}	1.78^{bc}	1.89	0.7	0.76	0.78	0.73	0.83	0.72	0.75
Mean	1.94	1.95	1.88	1.93	2.07	1.77		0.81	0.78	0.75	0.75	0.81	0.71	

* Within each column, values followed by the same letter are not significantly different at $p < 0.05$ level.

range test (DMRT) at a 0.05 significance level.

Results

Physiological Parameters

No significant difference was observed in the photosynthetic pigment of total chlorophyll and carotenoid contents of rice due to irrigation and nutrient management practices. However, AWD_{15} recorded the higher mean content of total chlorophyll in both years over CF (Table 1). The interaction of irrigation and nutrient management was found to be significant in year 1, with the highest contents at the $AWD_{15} \times S_1$ combination, and pooled data also showed the same trend. The same trend was noticed in the MDA content also. But higher production of MDA in CF irrigation was recorded in year 2 (9.25 micro-mol/g), followed by AWD_{15} (7.88 micro-mol/g), which was significantly different (Table 2). The pooled data also showed a similar effect with higher MDA activity in CF irrigation practice (9.95 micro-mol/g) over AWD_{15} (8.90 micro-mol/g), and no significant difference owing to nutrient management factors, and also due to the interaction of both factors, was observed (Table 2). Relative water content was found to be the highest in the AWD_{15} regime, which was 12% higher than the relative water content of CF (66%) as per pooled data analysis (Table 2); however, nutrient management and the interaction effect were observed to be non-significant due to pooled data.

Yield attributes

Alternate wetting and drying recorded significantly higher density of panicles in both years over CF. The pooled data showed a similar trend of higher panicle density at AWD_{15} with an increase of about 13% over the CF regime (Table 3). Among the nutrient management factors, no significant difference was noticed between the treatments in both years and in the pooled data. No significant interaction due to irrigation regimes and nutrient management factors was noticed in both years (Table 3). Data on grain-filling ratio revealed that the highest grain filling was observed in AWD_{15} at 84.14% compared to CF (75.96%) in year 1 (Table 4), and no significant difference was noticed in year 2 owing to irrigation practices. Due to nutrient management factors, S_2 recorded the highest filling ratio of 85.63 and was on par with other treatments except S_1. Pooled data showed no significant difference due to irrigation regimes with regard to grain filling ratio (Table 4).

Grain yield

Grain yield was found to be higher in continuous flooded irrigation (6245 kg/ha) in year 1, which was 17 percent higher than AWD_{15} (5163 kg/ha). Among the different nutrient management practices, the mean yield was found to be highest in S_5 (6258 kg/ha), followed by S_6 (6201 kg/ha), and the lowest yield of 4265 kg/ha was recorded in S_1 (Table 4). In the second year, the grain yield was not found significantly different between CF (5416 kg/ha) and AWD_{15} (5314 kg/ha) regimes. Among nutrient management practices, the highest grain yield was observed due to S_5 (5837 kg/ha), followed by S_4 (5445 kg/ha) and S_3 (5372 kg/ha). The lowest yield was recorded in S_6 (5107 kg/ha), which was on par with S_1 (5152 kg/ha). No significant interaction due to irrigation and nutrient management practices was observed in both years. In the pooled analysis, an increase in grain yield of 10% was observed in CF (5830 kg/ha) compared to AWD_{15} (5238 kg/ha). Among the nutrient management factors, S_5 recorded the highest grain yield of 6048 kg/ha, followed by S_4 (5758 kg/ha), and the treatments S_2, S_3, and S_6 were statistically on par with S_4 (Table 4). No significant interaction was noticed between irrigation

Table 2: Effect of irrigation regimes and nutrient management factors on malondialdehyde and relative water content.

	Malondialdehyde content (micro-mol g^{-1})							Relative water content (%)						
Year 1														
Treatments	S_1	S_2	S_3	S_4	S_5	S_6	Mean	S_1	S_2	S_3	S_4	S_5	S_6	Mean
AWD_{15cm}	8.60	12.51	11.98	5.31	6.73	14.37	9.92	63.60	65.19	72.21	74.25	68.52	56.79	66.76
CF	6.98	15.21	11.14	12.70	10.93	6.93	10.65	70.42	41.91	61.72	62.98	67.78	43.44	58.04
Mean	7.79	13.86	11.56	9.01	8.83	10.65		67.01	53.55	66.97	68.61	68.15	50.11	
Year 2														
AWD_{15cm}	8.99^{abc}	9.58^{ab}	6.58^{cd}	6.23^{d}	8.66^{abcd}	7.27^{bcd}	7.88^{b}	77.60	82.92	80.29	78.58	79.31	89.16	81.31^{a}
CF	6.42^{cd}	9.60^{ab}	8.69^{abcd}	9.38^{ab}	10.3^{a}	11.09^{a}	9.25^{a}	74.63	77.79	71.88	77.87	78.71	69.57	75.08^{b}
Mean	7.70	9.59	7.64	7.80	9.48	9.18		76.12	80.35	76.09	78.22	79.01	79.37	
Pooled data														
AWD_{15cm}	8.8	11.04	9.28	5.77	7.69	10.82	8.90^{b}	70.6	74.05	76.25	76.41	73.92	72.97	74.03^{a}
CF	6.7	12.4	9.92	11.04	10.62	9.01	9.95^{a}	72.53	59.85	66.8	70.43	73.24	56.51	66.56^{b}
Mean	7.75	11.72	9.6	8.4	9.16	9.92		71.56	66.95	71.53	73.42	73.58	64.74	

* Within each column, values followed by the same letter are not significantly different at $p < 0.05$ level.

regimes and nutrient management factors.

Water productivity

The water productivity showed different responses in both years. CF was observed with the higher WP in year 1 (0.31) over $AWD1_5$ (0.27), whereas in year 2, AWD_{15} was noted with the highest WP of 0.44 over CF (0.39), and both were significantly different. Among the nutrient management factors, S_5 resulted in the highest WP of 0.32, and the other treatments were on par with S_5, such as S_4 (0.31), S_6 (0.31), S_2 (0.29), and S_3 (0.29) in year 1. Similarly, in the second year, S_5 was found with the highest WP of 0.45. In both years, S_1 was recorded with the least WP (Table 3). However, pooled analysis showed that AWD_{15} had the highest WP of 0.36 over the CF regime (0.35), which was significantly different. Moreover, S_5 had the highest WP (0.39) among the nutrient management factors, followed by S_4, S_6, S_2, and S_3, and the lowest WP was recorded in S_1. No significant interaction was observed owing to the irrigation and nutrient management factors in both years and in the combined data.

Discussion

Effect of irrigation regimes and nutrient and soil management factors on physiological parameters

The observed photosynthetic pigments revealed that implementing the AWD regime had no significant effect on total chlorophyll and carotenoid content in rice crops, even after experiencing minor water stress during different phases of growth, compared to the well-watered CF regime. According to Wichaidist *et al*., (2025a), three irrigation regimes, namely, CF, AWD, and saturated soil irrigation (SSI), did not significantly alter the photosynthetic pigment content of chlorophyll and carotenoids in rice. It was noted that the AWD regime combined with different nutrient management resulted in higher chlorophyll and carotenoid levels than the CF regime. Water stagnation in the soil throughout the crop growth stages due to CF irrigation may have hindered nutrient uptake and the subsequent formation of photosynthetic pigments. A similar conclusion was made by Insulad *et al*., (2006), as rice plants showed reduced nutrient uptake from stagnant conditions due to a lack of oxygen compared to aerated soil, resulting in reduced growth metrics. These results imply that conservative irrigation practices such as AWD could replace conventional flooded irrigation practices, that it will not affect photosynthetic efficiency beyond the threshold where growth inhibition occurs, and also the potential of AWD practices to maintain growth and yield of rice.

Continuous flooding regime increased MDA production in both years, suggesting that AWD methods may have evolved to withstand water stress and minimise cellular damage. Reduction in MDA content was noticed in AWD over CF regime and it may be due to the crops' better ability to scavenge reactive oxygen species (ROS) through increased activity of primary antioxidant enzymes (Qi *et al*., 2024, Wichaidist *et al*., 2025b), and lack of oxygen uptake during CF irrigation may accumulate more ROS, resulting in lipid peroxidation and the formation of higher MDA in rice (Bu *et al*., 2025). The use of ammonium sulphate in this study under both irrigation systems contributed to increased mean MDA content, which could be related to the availability of more ammonia in soil and subsequent toxicity due to overproduction of extra free radicals and cell damage on its uptake (Gao *et al*., 2019; Haung *et al*., 2022; Yang *et al*., 2023).

Compared to flooded irrigation, AWD showed a greater relative water content status even after drying periods at different crop phases. This suggests that plants

Table 3: Effect of irrigation regimes and nutrient management factors on water productivity and panicle density.

	Water productivity (kg m^{-3})							Panicle density (panicles m^{-2})						
Year 1														
Treatments	S_1	S_2	S_3	S_4	S_5	S_6	Mean	S_1	S_2	S_3	S_4	S_5	S_6	Mean
AWD_{15cm}	0.20	0.27	0.28	0.29	0.29	0.29	0.27^{b}	457.33	469.33	419.00	449.33	485.33	420.67	450.17^{a}
CF	0.23	0.31	0.30	0.32	0.34	0.34	0.31^{a}	366.67	377.33	396.67	344.00	430.67	372.33	381.28^{b}
Mean	0.22^{b}	0.29^{a}	0.29^{a}	0.31^{a}	0.32^{a}	0.31^{a}		412.00	423.33	407.83	396.67	458.00	396.50	
Year 2														
AWD_{15cm}	0.42	0.42	0.44	0.45	0.48	0.42	0.44^{a}	397.67	435.33	327.33	380.33	397.33	379.67	386.28^{a}
CF	0.38	0.40	0.39	0.40	0.42	0.38	0.39^{b}	352.33	357.33	339.33	344.67	353.67	320.33	344.61^{b}
Mean	0.40^{cd}	0.41^{bcd}	0.42^{bc}	0.42^{b}	0.45^{a}	0.40^{d}		375.00^{ab}	396.33^{a}	333.33^{c}	362.50^{b}	375.50^{ab}	350.00^{bc}	
Pooled data														
AWD_{15cm}	0.31	0.35	0.36	0.37	0.39	0.35	0.36^{a}	427.5	452.33	373.17	414.83	441.33	400.17	418.22^{a}
CF	0.3	0.35	0.34	0.36	0.38	0.36	0.35^{b}	359.5	367.33	368	344.33	392.17	346.33	362.94^{b}
Mean	0.31^{c}	0.35^{b}	0.35^{b}	0.37^{b}	0.39^{a}	0.36^{b}		393.50^{abc}	409.83^{a}	370.58^{d}	379.58^{bcd}	416.75^{ab}	373.25^{cd}	
* Within each column, values followed by the same letter are not significantly different at $p < 0.05$ level.														

may not have been stressed to the threshold level of yield loss even after reducing the volume of water provided over CF irrigation. This greater RWC under conservative irrigation techniques such as AWD in rice could be explained by a number of factors. Plants' adaptation to establish deeper and denser roots in response to recurrent flooding-drying-reflooding cycles enables them to collect moisture from deeper soil layers (Chu *et al*., 2018; Song *et al*., 2018). The partial closure of stomata during dry phases to limit water loss by transpiration keeps a higher relative water content (Zhang *et al*., 2025).

Effect of irrigation regimes and nutrient and soil management factors on yield attributes and yield

A positive response was received from the trial on the density of panicles under the conservative irrigation practice of AWD compared to CF. It suggests that reducing irrigation, provided the drying cycles are optimal, results in a higher number of productive tillers. Alternate wetting and drying has a tendency to reduce the total number of tillers compared to flooded irrigation, and hence alternate drying periods increase the number of productive tillers and proportion of leaf area, which further reduces the unproductive vegetative growth in rice (Yang and Zhang, 2010; Yang *et al*., 2017; Li *et al*., 2024). Application of ammonium sulphate has given a promising effect on higher density of tillers, which might be the effect accrued on dual availability of nitrogen and sulphur. Application of ammonium sulphate in lowland rice had a higher number of productive tillers due to the availability of nitrogen and sulphur in an available form, especially in sulphur-deficient soils, compared to urea application as a nitrogen source (PAPRiz, 2013). A similar trend was found with regard to grain filling ratio under AWD regime, and a higher grain filling in alternate drying practice could be associated with the aeration status of the soil compared to CF. Highly oxidized soils tend to develop deep and larger root biomass, which in turn mobilizes carbon

Table 4: Effect of irrigation regimes and nutrient management factors on grain filling ratio and grain yield.

	Grain filling ratio (%)							Grain yield (kg ha^{-1})						
Year 1														
Treatments	S_1	S_2	S_3	S_4	S_5	S_6	Mean	S_1	S_2	S_3	S_4	S_5	S_6	Mean
AWD_{15cm}	75.88	88.47	83.66	84.73	86.72	85.37	84.14^{a}	3873	5117	5380	5547	5530	5530	5163^{b}
CF	64.08	82.79	74.87	82.33	74.31	77.39	75.96^{b}	4657	6307	6057	6593	6987	6870	6245^{a}
Mean	69.98^{b}	85.63^{a}	79.27^{a}	83.53^{a}	80.52^{a}	81.38^{a}		4265^{b}	5712^{a}	5718^{a}	6070^{a}	6258^{a}	6200^{a}	
Year 2														
AWD_{15cm}	81.25	80.20	83.41	88.95	90.11	89.24	85.53	5093	5140	5413	5453	5867	5053	5337
CF	87.75	91.06	83.38	92.41	84.34	94.12	88.84	5210	5430	5680	5487	5913	5203	5487
Mean	84.50^{c}	85.63^{bc}	83.40^{c}	90.68^{ab}	87.22^{abc}	91.68^{a}		5152^{c}	5285^{bc}	5547^{b}	5470^{b}	5890^{a}	5128^{c}	
Pooled data														
AWD_{15cm}	78.56	84.33	83.54	86.84	88.42	87.3	84.83	4483	5128	5397	5500	5698	5292	5250^{b}
CF	75.92	86.92	79.13	87.37	79.32	85.75	82.4	4933	5868	5868	6040	6450	6037	5866^{a}
Mean	77.24^{c}	85.63^{ab}	81.33^{bc}	87.11^{a}	83.87^{ab}	86.53^{a}		4708^{c}	5498^{b}	5633^{b}	5770^{b}	6074^{a}	5664^{b}	
* Within each column, values followed by the same letter are not significantly different at $p < 0.05$ level.														

reserves towards kernels, and higher yield (Setyanto *et al*., 2018). Grain production was shown to be higher in the CF regime in both years compared to AWD. Alternate drying phases helped the crop to retain steady levels of photosynthetic pigments, malondialdehyde, and relative water content even under mild stress, resulting in equivalent grain yields in both irrigation methods. According to various authors, AWD practices have resulted in comparable grain yield over flooded irrigation practices, along with the additional benefit of the mitigation potential of greenhouse gases in rice (Howell *et al*., 2015; Arai *et al*., 2021; Mote *et al*., 2023; Hoang *et al*., 2023; Loaiza *et al*., 2024). The highest mean yield was obtained in both years when lime and phosphogypsum were applied in a 3:1 ratio along with the recommended dose of fertilizers, both under CF and AWD regimes. The soil amelioration effect of lime combined with the availability of vital nutrients like Ca, Mg, S, and P upon phosphogypsum inclusion may have contributed to the higher yield in rice. Similar results of application of the lime and phosphogypsum improving the pH of surface soil and increasing the availability of vital elements in the soil, with increased grain yield in rice were reported (Soratto and Crusciol, 2008; Duart *et al*., 2021). Furthermore, the use of diammonium phosphate resulted in lower yields in both years, with the effect being more obvious under flood irrigation. This yield drop could be related to the availability of ammonia in excess as a nitrogen source during submergence and the consequent toxicity to rice plants by reduced root respiration and growth of root hairs, nutritional imbalance, disruption of cellular pH equilibrium, and oxidative stress (Bittsanszky *et al*., 2015; Gao *et al*., 2019; Podgorska *et al*., 2021; Yang *et al*., 2023).

Effect of irrigation regimes and nutrient and soil management factors on water productivity

Implementing AWD irrigation contributed to higher WP than CF over two years of pooled data analysis. However, the variability accrued between years might be due to changes in environmental conditions and associated water consumption. Comparable yield was obtained under AWD, along with higher WP, clearly indicating that sustainable rice growth with reduced irrigation water upon implementing AWD is a promising technology to improve global water productivity. Similar conclusions were made that AWD yielded comparable grain to CF in rice cultivation with higher water productivity (Sriphirom *et al*., 2019; Johnson *et al*., 2024). There was no interaction effect with irrigation regimes and nutrient management factors. However, S_5 treatment received with lime and phosphogypsum had shown higher WP; it could be due to the higher yield obtained under both irrigation methods on the soil amelioration effect attained from the soil amendments, along with the availability of plant nutrients from it (Kumar *et al*., 2020). This emphasizes the importance of conservative irrigation practices along with soil amendments in helping improve rice intensification globally with reduced irrigation water consumption.

Conclusion

Intense irrigation requirements in rice put pressure on the water requirements of non-agricultural sectors, and this has led to the development of policies to shift towards less water-requiring crops such as millets, oilseeds, and pulses globally. However, this shift may further pose significant risks to food security around the world, especially in Asian countries. So, this scenario could be handled by introducing conservative irrigation practices like AWD, which require less water compared to traditional continuous flooded irrigation in rice. This study indicated that AWD irrigation regime could reduce water consumption in rice compared to the CF method, with favourable physiological performance and negligible impact on crop yield. The study also highlights that AWD practice could safely be substituted for the CF method of irrigation with considerable effect on water conservation and increased water productivity.

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