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Water and Crop Management Technologies: Physiological Response and Yield of Biofortified Rice

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Abstract

Biofortified rice has emerged as one of the most promising strategies to enhance the micronutrient content of staple crops, offering a practical pathway to reduce stunting and improve nutritional security. In response to the challenges posed by climate change, water scarcity, and the need for more efficient production systems, this study examined the effects of water- and crop-management technologies on the physiological performance and yield of biofortified rice. A factorial randomized complete block design compared continuous flooding and alternate wetting and drying (AWD) irrigation with two crop management systems: conventional and a new technology. The AWD system enhanced photosynthesis without significantly affecting transpiration or stomatal conductance, indicating improved carbon assimilation and more efficient water use. Both AWD and the new technology individually increased dry grain yield per clump, while their combination produced heavier grains, higher productivity, greater 1000-grain weight, and improved water-use efficiency compared with other treatments. Although yield differences were not statistically significant, the consistent upward trends indicate synergistic potential when nutrient management is optimized. Overall, integrating AWD irrigation with new technology crop management can enhance resource efficiency in biofortified rice cultivation while maintaining yield stability under water-limited conditions.

Keywords: alternate wetting and drying, climate-smart farming, food crop, irrigation, sustainable production

Introduction

The challenge of feeding the world requires producing food that is both high-quality and in sufficient quantity. Climate change severely disrupts food production (Berhane, 2018; Tchonkouang et al., 2024), threatening global food security (Mirzabaev et al., 2023). This crisis intensifies the urgent need to combat stunting caused by nutrient-deficient diets, with Indonesia facing a national prevalence of 20.1% among children under age two (Laksono et al., 2022; UNICEF & Ministry of Health of the Republic of Indonesia, 2024).

Biofortified rice offers a promising strategy to boost micronutrient content in staple crops (Bouis et al., 2024; Majumder et al., 2019). Rice dominates Indonesian diets, consumed by over 90% of the population, with demand projected to rise from 25.6 million tons in 2017 to 28.2 million tons in 2025 and 31.7 million tons in 2045 (Arifin et al., 2019). NutriZinc, Indonesia's first lowland biofortified rice variety released in 2019 (Decree of the Minister of Agriculture No. 168/HK.540/C/01/2019; Indonesian Ministry of Agriculture, 2023), contains 25% more zinc than conventional varieties and exemplifies solutions for nutritional and climate resilience (Kamruzzaman et al., 2025). Optimizing

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cultivation technologies for NutriZinc remains essential for widespread adoption.

Rice production faces rising demand, water scarcity, and climate impacts, yet intensification exacerbates environmental costs by requiring high water and energy inputs. One kilogram of rice requires 800–5,000 L of water (average 2,500 L), which is two to three times more than other cereals (Surendran et al., 2021; Yao et al., 2017). Traditional continuous flooding amplifies this inefficiency. Alternate wetting and drying (AWD) provides a simple, low-cost irrigation method that maintains yields while cutting water use by 33.88%, boosting water productivity by 29.63%, and improving efficiency by 47.58% globally (Gao et al., 2024; Ishfaq et al., 2020). AWD reduces methane emissions by 47.47% and slightly increases N_2O emissions by 52.20%; net effects include a 39% lower global warming potential and a 38% reduction in greenhouse gas intensity (Gao et al., 2024). This approach enhances climate adaptation and sustainability (Anschell & Salamanca, 2021; Lampayan et al., 2015).

Sustainable practices such as slow- or controlled-release fertilizers, water-saving irrigation, and no-till farming minimize greenhouse gas emissions without yield losses (Zhang et al., 2024). The PPAI Technology® package targets these needs through 10 interventions for rice: certified seeds, straw decomposers, micronutrients, biological agents, silica fertilizer, reduced use of insecticides and herbicides, mycorrhizae, booster fertilizers, and AWD—offering eco-friendly alternatives to conventional methods while boosting productivity and resilience.

This study evaluates the effects of water and crop management technologies on the physiological responses and yields of biofortified rice (NutriZinc) under Indonesian conditions. Despite rice's staple role, water inefficiency and stunting persist, and prior testing of integrated strategies has been limited locally. Results will inform practices enhancing food security, nutrition, and environmental sustainability.

Materials and Methods

Time, Site, and Experimental Design

The research was conducted from June to November 2024 in Banyuwangi Regency, East Java Province, Indonesia. The study employed a factorial randomized complete block design with four replications. The first factor was water management technology, consisting of two methods: continuous flooding and alternate wetting and drying (AWD). The second factor was cropping management technology, which comprised two methods: conventional and PPAI Technology®, hereinafter referred to as the new technology. Each experimental unit measured 10 m × 10 m and was planted with three 14-day-old rice seedlings per hill using a 2:1 alternating row planting system (50 cm × 25 cm × 12.5 cm), resulting in a total plant population of approximately 1,200.

Water and Crop Management Technology

Water management was regulated through controlled irrigation. The continuous irrigation method maintained flooded conditions throughout the growing season, whereas the alternate wetting and drying (AWD) method opened the irrigation channel, allowing water to rise to approximately 10 cm above the soil surface. The field was then left without additional irrigation for 5–6 days, during which the water level decreased naturally through evapotranspiration and plant water use. Irrigation was reapplied when the water level reached approximately 10 cm below the soil surface, creating a controlled dry-down period.

Conventional crop management represented the standard practices applied by local farmers for rice cultivation. In contrast, the new technology crop management refers to an improved set of interventions designed to enhance productivity and sustainability. These interventions included certified seeds, straw decomposer, complete micronutrients, biological agents, silica fertilizer, insecticide reductant, herbicide reductant, mycorrhizae, and booster fertilizer.

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The insecticide reductant, Pest Solution® (PS), is a formulation that enhances the efficacy of insecticides by increasing the permeability of pest cell membranes, thereby accelerating the absorption of active ingredients. The synergistic combination of chitosan and quercetin in PS disrupts pest metabolism, causing physiological stress that weakens pests and maximizes insecticide performance. The antifeedant effect of PS further inhibits pest feeding behaviour, alters their life cycle, and contributes to long-term pest control. Similarly, WEED Solut-ioN® (WS) is an herbicide reductant that reduces herbicide dosage by up to 50% while maintaining efficacy by amplifying the activity of the herbicide's active ingredients. Details of the conventional and PPAI Technology® management packages are presented in Table 1.

Table 1

Conventional and the New Innovative Technology Packages

No	Input	Conventional	New technology[1]
Nutrient			
1	Urea (12 and 34 DAP)	250 kg/ha	175 kg/ha
2	NPK 15-10-12 (12 and 34 DAP)	250 kg/ha	200 kg/ha
3	Starter fertilizer	No	300 kg/ha
4	Mycorrhiza	No	0.5 kg/35kg seed applied during the seedling stage; 1.5 kg/ha mixed with fertilization (12 DAP)
5	Silica (45 DAP)	1.5 L/ha	1.5 kg/ha
6	Micronutrient (59 and 69 DAP)	No	2.5 $g{\bullet}L^{-1}{\bullet}ha^{-1}$
Herbicide and WEED Solut-ioN® (WS) applied at 14 DAP			
7	Pre-emergence herbicide 2.4-D Dimethylamine	150 g/ha	75 g/ha
8	Pre-emergence herbicide methyl chlorimuron + 2,4-D sodium	20 g/ha	10 g/ha
9	WS	No	85 ml/ha
Insecticide, fungicide, and pesticides** applied at 34, 49, 56, 58, 65, 76 DAP			
10	Fipronil	300 ml/ha	150 ml/ha + Pest Solution 150 ml/ha
11	Dimehipo	560 ml/ha	280 ml/ha + Pest Solution 280 ml/ha
12	Nitenpyram	200 ml/ha	100 ml/ha + Pest Solution 100 ml/ha
13	Pymetrozine	300 ml/ha	150 ml/ha + Pest Solution 150 ml/ha
14	Copper oxide	200 ml/ha	100 ml/ha + Pest Solution 200 ml/ha
Biological agents applied at 17, 27, 41, 55, 70, 83 DAP			
15	Metarhizium + *Beauveria bassiana*[2]	No	100 – 200 ml/ha
16	*Lecanicillium lecanii*[3]	No	100 – 200 ml/ha
17	*Paenibacillus*[4]	No	100 – 200 ml/ha
Straw and compost			
18	Return straw and composted material before soil tillage	No	Yes

Note. [1]PPAI Technology®; [2]BioMet; [3]BioLec; [4]BioCor

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Photosynthesis, Transpiration, and Stomatal Conductance Measurements

Photosynthesis, transpiration, and stomatal conductance were measured using a LI-COR portable photosynthesis system (LI-6400XT, LI-COR Inc., Lincoln, NE, USA), a widely used instrument for assessing gas exchange in plants. Measurements were conducted between 07:00 and 11:00 a.m. to minimize the effects of midday stomatal closure and to ensure stable environmental conditions. Each replication consisted of five plants, and measurements were taken from the two uppermost fully expanded leaves of each plant to capture optimal physiological activity.

Yield Characters and Production

Plants were harvested at 91 days after planting (DAP), and ten plants were selected as samples for yield character observations. The total number of grains per panicle was determined by counting the grains from three randomly selected panicles of ten sampled plants. The counted grains were then separated into filled and unfilled categories to calculate the proportion of filled and unfilled grains. The 1,000-seed weight was measured by randomly weighing a subsample of 1,000 grains collected from the total grain yield of the ten sampled plants. Grains from the same ten plants were also weighed to determine the dry-harvested grain weight per clump and the sun-dried, adjusted-to-approximately 14% seed moisture content grain weight per clump. Yield per plot was determined by weighing all harvested grains from the entire population within each 10 m × 10 m plot.

Water Use Efficiency

Water use efficiency (WUE) was calculated using the following formula:

$$\mathrm{WUE} = \frac{\text{Grain yield (kg/ha)}}{\text{Water volume (L)}}$$

The volume of water used was determined from the measured transpiration rate (mol•m^{-2}•s^{-2}), which was subsequently converted to water volume per hectare per season over the 91-day growing period. The conversion was performed using the equation below:

$$\text{Water volume (L/ha per season)} = \frac{(\text{Transpiration rate mol} \bullet \text{m}^{-2} \bullet \text{s}^{-2}) \times \text{ Molar mass of water (18.015 g/mol)}}{1000} x \frac{\text{Total land area (10,000 m}^2) \times \text{ Seconds in 91 days (7,862,400 s)}}{1000}$$

Data Analysis

Data were analyzed using analysis of variance (ANOVA) through the *F* test in SAS OnDemand for Academics at a significance level of 0.05; the LSD test was used to compare among treatments.

Results and Discussion

Photosynthesis, Transpiration, and Stomatal Conductance

The interaction between water and crop management technologies significantly affected the photosynthetic rate of biofortified rice, whereas no significant effects were observed on transpiration rate or stomatal conductance (Table 2). The alternate wetting and drying (AWD) treatment, when combined with either conventional or new technology-based crop management, resulted in higher photosynthetic rates (26.63–26.67 μmol•m^{-2}•s^{-1}) than continuous irrigation (22.84–23.98 μmol•m^{-2}•s^{-1}). However, neither water management nor crop management as individual factors significantly influenced any of the physiological response variables measured (Figure 1).

These results indicate that the increase in photosynthetic rate was influenced by the interaction between water and crop management rather than by either single factor. The higher photosynthetic rate observed under AWD, regardless of crop management practice, suggests that AWD can enhance carbon assimilation. The data also showed that AWD did not significantly affect transpiration rate or stomatal conductance, indicating that the increase in photosynthesis did not lead to excessive water loss.

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Table 2

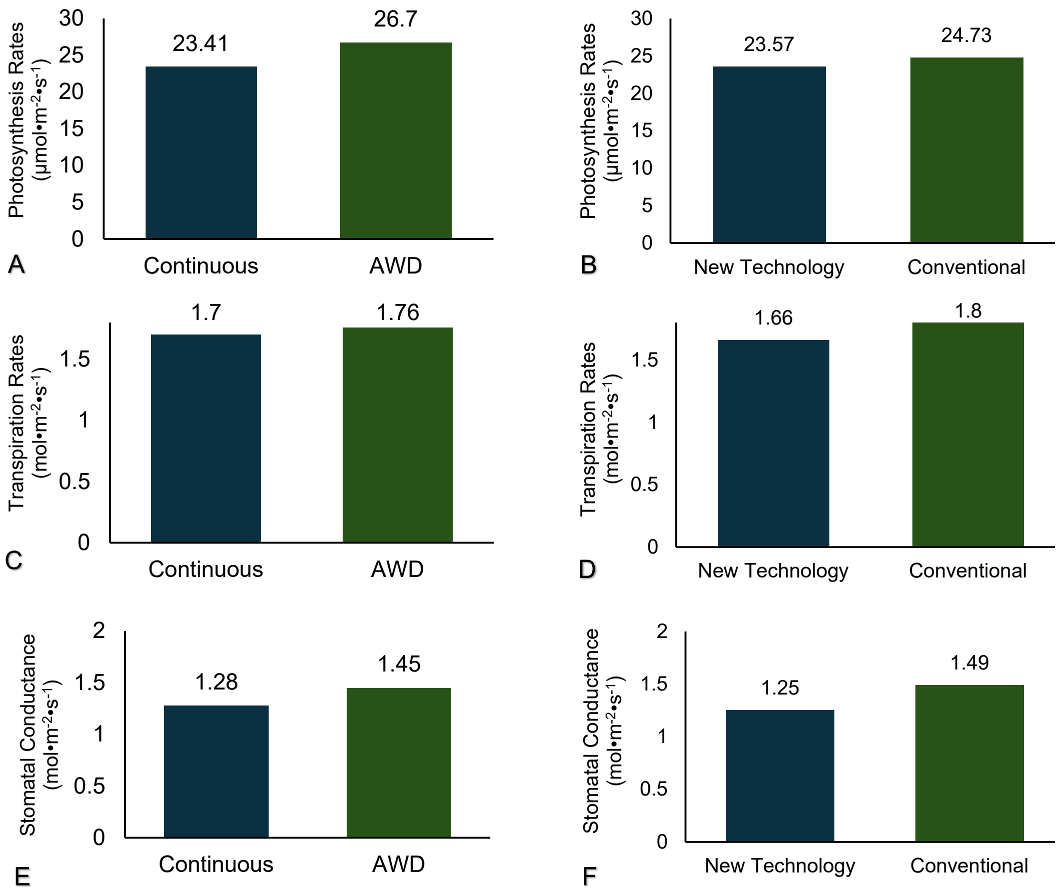
The Interaction of Water and Crop Management Technologies' Effect on Photosynthesis Rate, Transpiration Rate, and Stomatal Conductance of Biofortified Rice

Water management	Crop management	Photosynthesis rate (mol•m^{-2}•s^{-2})	Transpiration rate (mol•m^{-2}•s^{-2})	Stomatal conductance (mol•m^{-2}•s^{-2})
Continuous flooding	Conventional	22.84 b	1.81	1.54
	New technology	23.98 ab	1.59	1.03
Alternate wetting and drying	Conventional	26.63 a	1.79	1.44
	New technology	26.76 a	1.72	1.47

Note: The average value followed by the same letter(s) in the same column and row is not significantly different based on the LSD test with α = 0.05.

Figure 1

The Physiological Response of Biofortified Rice to Different Water and Crop Management Technologies



Note. A) photosynthesis rates of continuous and AWD, B) photosynthesis rates with conventional and the new technology, C) transpiration rates of continuous flooding and AWD.

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In several previous studies, AWD was reported to decrease photosynthesis, transpiration, and stomatal conductance. However, our results showed that AWD did not reduce these parameters compared with continuous irrigation. Similar findings were reported in *Tulipa edulis*, where AWD did not decrease photosynthetic rate compared to the control (Miao et al., 2015). This outcome may be associated with a regulatory mechanism involving stomatal conductance and abscisic acid (ABA), which is produced under drought stress to regulate stomatal closure (Ahmadi et al., 2010; Li et al., 2006). Such a mechanism may help rice maintain photosynthetic activity under water-limited conditions. Overall, these findings suggest that AWD can be applied as a water-efficient irrigation strategy for biofortified rice cultivation, optimizing photosynthetic performance while maintaining plant water balance.

Moreover, the effects of the single factors shown in Figure 1E indicate that there were no significant differences in photosynthetic rate, transpiration rate, or stomatal conductance. However, stomatal conductance under the AWD treatment tended to be higher than under the continuous flooding treatment. The mild, transient stress induced by AWD is presumed to trigger adaptive responses in plants, thereby improving water-use efficiency, enhancing root activity, and preventing hypoxic conditions. As a result, the stomata remain actively open during favourable periods, such as when the field is flooded.

This interpretation is supported by Wang et al. (2024), who reported that under moderate AWD conditions, both photosynthetic rate and mesophyll conductance increased—two key factors influencing the overall gas exchange capacity, including stomatal and internal leaf conductance, in plants. These findings emphasize that measuring physiological parameters at appropriate intervals is crucial under AWD treatments to accurately assess plant responses during both dry and flooded phases. Additionally, evaluating ABA biosynthesis or ABA content under these conditions is important, as ABA plays a central role in regulating stomatal behaviour and significantly affects gas exchange processes.

Stomatal conductance represents the regulation of gas exchange that governs CO_2 uptake for photosynthesis and water loss through transpiration (Vialet-Chabrand et al., 2017). It is closely influenced by several environmental factors, including temperature (Driesen et al., 2020; Pernicová et al., 2024), light intensity (Idris et al., 2019; Wild & Wolf, 1980), atmospheric CO_2 concentration (Driesen et al., 2020; Engineer et al., 2016; Pernicová et al., 2024; Purcell et al., 2018; Woodward & Kelly, 1995), humidity (Driesen et al., 2020), and soil water availability (Anav et al., 2018; Wu et al., 2021).

Yield Characteristics of Biofortified Rice

Despite the potential benefits of AWD in optimizing photosynthesis and water use, neither the single factors (water or crop management) nor their interaction had a significant effect on the total number of grains per panicle (Table 3). However, both the individual factors and their interaction significantly influenced the proportion of empty grains. The new technology resulted in a higher percentage of empty grains than the conventional method, while AWD also increased the proportion of empty grains compared with continuous irrigation. Furthermore, the interaction between AWD and the new technology further elevated the percentage of empty grains.

The single factors did not significantly affect the proportion of filled grains, but their interaction did. The new technology recorded the lowest percentage of filled grains (approximately 81.0%). In contrast, when either AWD or the new technology was applied independently—the new technology under continuous irrigation or conventional management under AWD—the percentage of filled grains did not differ significantly from the conventional–continuous treatment. These results indicate that while AWD and the new technology individually support normal grain filling, their combined application may compromise this process under the conditions tested.

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Table 3

Yield Characters of Biofortified Rice under Different Water and Crop Management Technologies

Water management	Crop management		Average
	Conventional technology	New technology	
	Total grains panicles		
Continuous flooding	135.4	131.0	133.2
Alternate wetting and drying	124.0	140.1	132.0
Average	129.7	135.5	
	Filled grains (%)		
Continuous flooding	87.1 a	84.1 ab	85.6
Alternate wetting and drying	82.3 ab	81.0 b	81.7
Average	84.7	82.6	
	Empty grains (%)		
Continuous flooding	12.9 b	13.7 b	13.3 B
Alternate wetting and drying	15.7 b	19.9 a	17.8 A
Average	14.3 B	16.9 A	
	1000-seed weight (g)		
Continuous flooding	20.38 b	21.28 ab	20.83
Alternate wetting and drying	21.38 a	20.55 ab	20.96
Average	20.88	20.91	

Notes. The average value with the same lowercase letter(s) in the same column and row is not significantly different based on the LSD test at α = 0.05. The average value followed by the same capital letter(s) in the same column or row is not significantly different based on the LSD test with α = 0.05. AWD = alternating wetting and drying treatment.

The new technology uses lower urea doses than conventional practices, aiming to enhance nitrogen use efficiency while maintaining yield performance. Although reduced nitrogen input may lower nitrogen availability, the inclusion of starter fertilizers and mycorrhizal inoculants can effectively support early plant establishment and growth. Nonetheless, the performance of these amendments may be influenced by water availability and soil moisture dynamics associated with alternate wetting and drying (AWD) regimes, as observed in this study. Maintaining an optimal nitrogen dosage remains essential to sustain photosynthetic activity, vegetative development, and grain filling processes, which collectively determine yield performance.

Furthermore, the new technology integrates biological agents, including BioMet, BioLec, and BioCor, to enhance plant resilience and stress tolerance. These agents, however, may interact with hormonal signalling pathways, particularly abscisic acid (ABA), under AWD-induced stress conditions, potentially altering source–sink dynamics and grain filling efficiency. Previous studies have shown that certain beneficial microorganisms, such as *Beauveria bassiana* in tomato (Guo et al., 2024), *Malva parviflora* (Abdelhameed et al., 2024), and *Metarhizium* in *Phaseolus vulgaris* (Hu & Bidochka, 2021) and maize (Peterson et al., 2023), can induce ABA-mediated responses under water-limited conditions, highlighting the complex interplay between biological inoculants and plant stress physiology.

The single factors (water and crop management) did not significantly affect the 1,000-seed weight; however, their interaction did. The AWD–conventional treatment produced the highest 1,000-seed weight, which was significantly greater than that of the continuous–conventional treatment. This value was not significantly different from those of the continuous–new

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technology and AWD–new technology. These results suggest that AWD under conventional management can improve 1,000-seed weight, although its effect is comparable to that of the new technology under continuous irrigation. The higher 1,000-grain weight observed under AWD and new technology is likely a contributing factor to the increased proportion of empty grains, as a larger sink capacity requires a proportionally greater source capacity (Wei et al., 2023).

Production of Biofortified Rice

Both the single factors and their interaction significantly increased the dry-harvested grain weight per clump and the sun-dried harvested grain weight per clump (Table 4). AWD increased both parameters compared with continuous irrigation, while the new technology also produced higher values than conventional crop management. Furthermore, the combination of AWD and the new technology resulted in the greatest dry and sun-dried harvested grain weights per clump among all treatments.

In contrast, neither the single factors nor their interaction had a significant effect on yield per plot, productivity, or harvest index. However, the AWD–the new technology combination tended to produce the highest yield, productivity, and harvest index, with values of 6.6 kg per plot, 5.1 t/ha, and 0.42, respectively. The other treatment combinations recorded yields ranging

Table 4

Production Biofortified Rice under Different Water and Crop Management Technologies with Alternate Wetting and Drying Treatment

Water management	Crop management		Average
	Conventional	New technology	
	Dry harvested grains per clump (g)		
Continuous flooding	28.5 b	31.6 b	30.1 B
Alternate wetting and drying	30.4 b	44.5 a	37.5 A
Average	29.5 B	38.1 A	
	Sun-dried dry harvested grains per clump(g)		
Continuous flooding	23.8 b	26.8 b	25.3 B
Alternate wetting and drying	24.6 b	35.4 a	29.9 A
Average	24.2 B	31.1 A	
	Yield per plot (kg)		
Continuous flooding	5.8	5.7	5.7
Alternate wetting and drying	6.0	6.6	6.3
Average	5.9	6.1	
	Productivity (t/ha)		
Continuous flooding	4.8	4.6	4.7
Alternate wetting and drying	4.6	5.1	4.8
Average	4.7	4.9	
	Harvest index		
Continuous flooding	0.40	0.38	0.39
AWD	0.34	0.42	0.38
Average	0.36	0.41	

Notes. The average value followed by the same lowercase letter(s) in the same column and row are not significantly different based on the LSD test with α = 0.05. The average value followed by the same capital letter(s) in the same column or row is not significantly different based on the LSD test with α = 0.05.

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from 5.7 to 6.0 kg per plot, productivity from 4.6 to 4.8 t/ha, and harvest index values between 0.34 and 0.40.

Water use Efficiency of Biofortified Rice

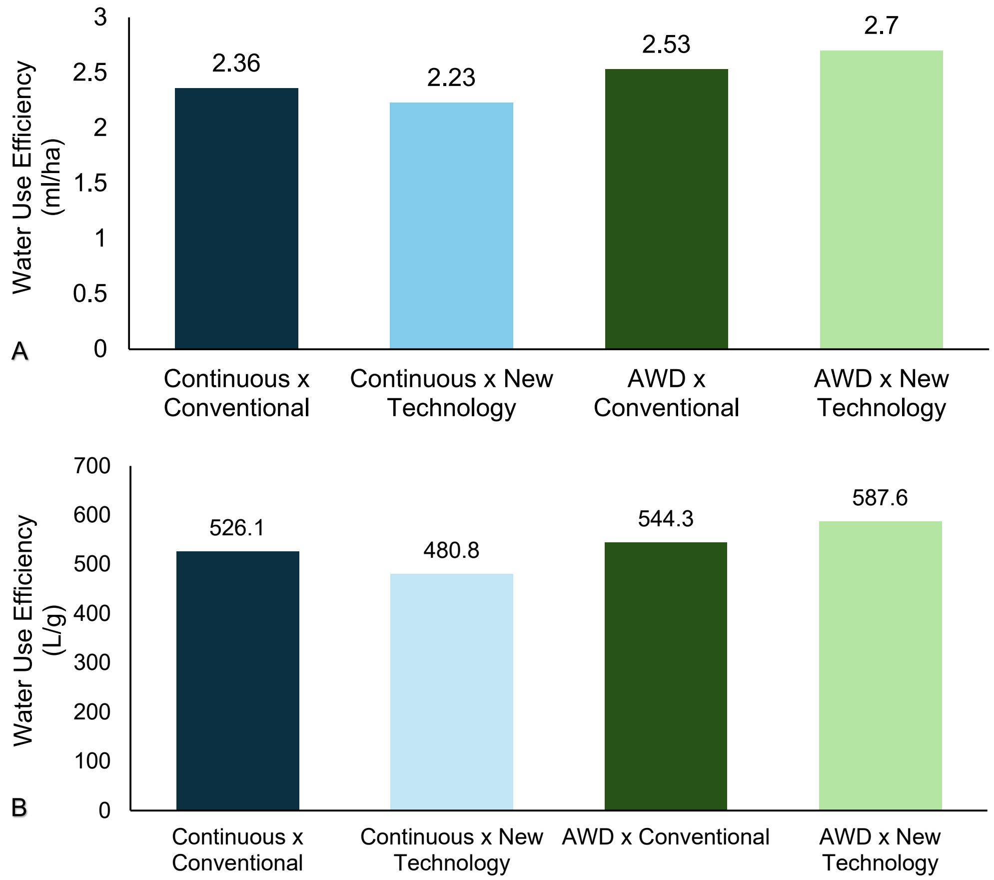
Water use in biofortified rice production ranged from change to “2230 to 2700 m^3/ha (based on land area) and from 0.49 to 1.05 gram rice per liter water” (based on grain yield) (Figure 2). Although no significant differences were observed among the treatment combinations, the AWD–new technology tended to exhibit higher water-use efficiency than the others, both on a land-area and yield basis.

In terms of total water consumption, the results of this study were consistent with those of Bouman et al. (2007), who reported that AWD irrigation reduced water use by approximately 15%–30% without causing a significant decrease in productivity. Similarly, Rahman and Bulbul (2014) found in Bangladesh that continuous flooding resulted in the highest water consumption but produced the lowest grain yield (4.7 t/ha) and lowest water use efficiency. In contrast, AWD treatments maintaining a water table 5–15 cm below the soil surface achieved lower water consumption, higher grain yield (5.7 t/ha), and greater water use efficiency.

Overall, the combination of AWD irrigation and the new technology crop management tended to improve water-use efficiency compared with other treatments. This finding provides an important basis for optimizing biofortified

Figure 2

Water Use Efficiency of Biofortified Rice Production Under Water and Crop Management Technologies



Notes. A) water use efficiency based on land area, B) water use efficiency based on rice production. AWD = alternating wetting drying treatment.

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rice production through more efficient water management. Beyond water use, AWD irrigation has also been widely recognized for its potential to mitigate greenhouse gas (GHG) emissions, particularly methane (CH_4), which is typically produced under continuously flooded conditions. By introducing intermittent drying periods, AWD promotes aerobic soil environments that suppress methanogenesis, thereby contributing to climate change mitigation. Further research is warranted to quantify this potential under biofortified rice cultivation systems.

Conclusions

This study demonstrates that water and crop management technologies influence both the physiological responses and yield characteristics of biofortified rice. Alternate wetting and drying irrigation and the new PPAI Technology® crop management each contribute to more resource-efficient and sustainable biofortified rice production. Alternate wetting and drying enhanced photosynthetic performance without significantly increasing transpiration or stomatal conductance, indicating improved carbon assimilation and water conservation efficiency. Alternate wetting and drying and the new technology individually increased dry grain yield per clump, while their combined application produced heavier grains, longer panicles, and higher water-use efficiency compared with other treatments. While the interaction lacked statistical significance, the sustained positive trends suggest a synergistic potential that may be realized through refined nutrient management. The slightly higher proportion of empty grains under alternate wetting and drying, and the new technology, reflect the need for improved nutrient synchronization under alternating moisture regimes rather than a limitation of the technologies themselves. Optimizing nitrogen and micronutrient management is expected to enhance grain filling to realize the full yield potential of this integrated system. Given the global importance of rice and the urgency of reducing water and chemical inputs in agriculture, these findings reaffirm the promise of combining alternate wetting and drying irrigation with the new technology crop management as a scalable pathway to improve resource efficiency, maintain yield stability, and strengthen both nutritional and climate resilience in rice-based farming systems. Future research should focus on optimizing nutrient synchronization and elucidating plant stress signalling pathways to strengthen the agronomic and physiological basis of this integrated approach.

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