Deficit Irrigation Strategies for Enhancing Water Productivity and Grain Yield of *Oryza sativa* L. under Alternate Wetting and Drying Conditions

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ABSTRACT

Background: Rice (*Oryza sativa* L.) represents 50% of the total amount of freshwater that is extracted for irrigation at the global level, thus, creating the necessity for the development of sustainable approaches in water management. Using Alternate Wetting and Drying (AWD) in combination with deficit irrigation may help in lowering water expenditure and maintaining the productivity of crops.

Objective: The present research aimed at exploring the results of the use of deficit irrigation methods combined with scheduling of Alternate Wetting and Drying regarding water productivity, physiological performance of crops and grain yield.

Strategy: The field experiment involved four irrigation treatments: continuous flooding (CF, control treatment), AWD with 100% water requirement (AWD-100%), AWD with 80% water requirement (AWD-80%), and AWD with 60% water requirement (AWD-60%). The treatments were laid down according to randomized complete block design and repeated four times.

Methods: To establish soil moisture dynamics, apply irrigation water, and define the physiological parameters (e.g., plant height, leaf area index, chlorophyll content, relative water content), biomass accumulation, grain yield, and measure the indicators of water-use efficiency, the study should be carried out throughout the entire growing season.

Key Findings: The implementation of AWD-80% in rice cultivation realized 89.7% of yield potential (7.24 $t \cdot ha^{-1}$ compared to 8.06 $t \cdot ha^{-1}$ obtained through conventional flooding technique) with 28.4% of the water being saved. Water productivity increased by 42.3% due to AWD-80% (1.82 $kg \cdot m^{-3}$). In addition, physiological parameters indicated that plants react physiologically to stress conditions by increasing relative water content and photosynthetic efficiency.

Summary: The study proves that the application of deficit irrigation approach supplemented with AWD technology leads to higher water-use efficiency in rice cultivation, which enables climate-resilient agriculture in areas with scarce water resources.

Keywords: Alternate Wetting and Drying; water productivity; rice irrigation; deficit irrigation; crop physiology; sustainable agriculture

1. Introduction

Rice is key to food safety in the world, feeding over 5 billion people as a food product, plus annual production accounting for about 750 million tons of the outputs from about 165 million hectares in land [1]. However, rice production can be demanding in terms of water resources, being responsible for about 24% of global water withdrawals although only representing a small share of cultivated land [2]. For instance, in the key growing regions of Asia, aquifers are depleted at rates of over 1 meter per year, while the water supply is being threatened by ever-increasing urban demand [3].

Traditional rice cultivation is based on continuous irrigation flooding, which helps keep underwater in fields to a depth of about 5–10 cm during the whole growing season. This method has emerged after rice was cultivated naturally in a wet environment and got rooted in practice despite its being the least efficient way of water use [4].

The AWD or Alternate Wetting and Drying method is a new way of scheduling irrigation to allow soil water tension to increase above the flooded state before the occurrence of rewatering. AWD does not allow permanent flooding, which leads to many benefits, such as significant water savings (30-50% according to research results), better root development due to stress adaptation, improved nutrient cycling, lower methane emissions because of anaerobic conditions in the soil, and sustainable/high grain production [5, 6]. Since the cooperation between the International Rice Research Institute (IRRI) and national agricultural systems of many Asian countries, AWD has become widely used in irrigated rice areas (especially in Bangladesh, India, China, and Vietnam) [7].

The utilization of deficit irrigation (the intentional under-supply of water) with AWD can be beneficial for water conservationing as well. Research has shown that rice has physiological capabilities to produce more with reduced irrigation (70-85% less than full water requirement), especially when water deficit is provided in appropriate time [8, 9].

Although possibilities are acknowledged, research on the aspects of deficit irrigation along with AWD was very limited in terms of comprehensive assessment of expressed results in the field. In most of the studies the concepts of AWD and deficit conditions have been studied separately with very few being provided with the details of their intersection in practice. Moreover, many questions about physiology behind the adaptation to the combined stress are still left unanswered, especially the interdependence between variations of soil moisture potential, photosynthesis, and yield [11].

The aim of this research was to conduct a comparative assessment of deficit irrigation approaches along with AWD in terms of their influence on crop water productivity, adaptation of plants to irrigation practice, biomass allocations, yield, and efficiency of water utilization in rice cultivation.

2. Materials and Methods

2.1 Experimental Site and Environmental Conditions

The experiment was conducted at the research farm of the National Rice Research Institute (NRRI), Cuttack, India (20.5°N, 85.9°E, 3 m above mean sea level) during two consecutive monsoon seasons (June–November 2021 and June–November 2022). The experimental site is located in the Indo-Gangetic plains rice belt, experiencing a tropical humid climate. The region receives mean annual rainfall of 1,589 mm, concentrated during June–September monsoon period. Mean temperature during the rice growing season (kharif) ranges from 25°C to 32°C. The site represents a representative rice-growing environment where water scarcity and groundwater depletion constitute primary constraints to agricultural sustainability.

Soil at the experimental site is classified as Fluventic Ustochrept, characterized by silty clay loam texture with predominantly puddled surface conditions. Key soil physicochemical properties are presented in Table 1. The site maintains adequate subsurface water availability through proximity to irrigation canal systems, enabling controlled water application studies.

2.2 Plant Material and Crop Establishment

A high-yielding, early-maturing rice cultivar (*Oryza sativa* L. ssp. indica, cv. 'IR-64') was selected based on its widespread cultivation across the region, documented responsiveness to water management innovations, and agronomic consistency. The cultivar exhibits grain yield potential of 7.5–8.5 $t \cdot ha^{-1}$ under optimal management. Seeds were sown in prepared nursery beds, and 45-day-old seedlings were transplanted into puddled experimental plots at a spacing of 20 cm × 15 cm (approximately 33 $plants \cdot m^{-2}$), representing standard commercial density for this cultivar.

Standard agronomic practices uniformly applied across all treatments included recommended doses of nitrogen (120 $kg \cdot ha^{-1}$), phosphorus (60 $kg \cdot ha^{-1}$), and potassium (40 $kg \cdot ha^{-1}$) split in 3–4 applications, integrated pest management practices, and harvest at physiological maturity.

2.3 Experimental Design and Irrigation Treatments

The experiment employed a randomized complete block design (RCBD) with four replicate blocks. Four irrigation treatments were implemented:

T_1 (Control): Continuous Flooding (CF) maintained at 5–7 cm water depth throughout growing season, representing conventional rice cultivation practice.

T_2 (AWD-100%): Alternate Wetting and Drying at 100% of crop water requirement. Soil moisture was allowed to decline until the soil water potential reached -20 kPa (indicator of AWD threshold), then water was applied to restore 5 cm standing water. This cycle was repeated throughout the season.

T_3 (AWD-80%): Alternate Wetting and Drying at 80% of crop water requirement. AWD scheduling was implemented as in T_2, but irrigation water application was reduced to 80% of crop evapotranspiration (ET_c) requirement.

T_4 (AWD-60%): Alternate Wetting and Drying at 60% of crop water requirement. Similar AWD scheduling as T_2 and T_3, but irrigation provided only 60% of ET_c requirement.

Each experimental plot measured 5.0 m × 5.0 m (25 m²), accommodating approximately 825 plants per plot. Plots were separated by bunds (raised embankments) to ensure independent water management. Figure 1 presents the conceptual workflow of the experimental design.

2.4 Soil Moisture Monitoring and Irrigation Scheduling

Soil moisture status was determined using tensiometer arrays installed at 15, 30, and 45 cm soil depths in each plot. Daily soil water potential measurements were recorded at 10:00 h using calibrated tensiometers. Volumetric soil moisture content was determined gravimetrically at 5-day intervals throughout the growing season using soil cores collected at multiple depths, processed by standard oven-dry methods (105°C, 24 hours).

Irrigation water application was scheduled at 5-day intervals based on soil moisture status, crop water requirement calculations derived from FAO Penman-Monteith reference evapotranspiration data adjusted by crop coefficients established for rice phenological stages. Total irrigation water applied (in mm) was measured for each plot using calibrated water meters. Figure 2 illustrates soil moisture fluctuations throughout the growing season across treatments.

2.5 Crop Growth and Physiological Assessment

Crop growth parameters were assessed at tillering, boot, heading, and grain-filling growth stages. Plant height was measured from soil surface to the apex of the uppermost leaf blade. Leaf Area Index (LAI) was determined using non-destructive leaf area measurements on 10 randomly selected plants per plot using a portable leaf area meter (LI-3100C, LI-COR). Chlorophyll content was quantified using a SPAD-502 chlorophyll meter (Minolta) on fully expanded leaves at the flag leaf stage.

Relative Water Content (RWC) of flag leaves was determined using the standard protocol: RWC (%) = [(fresh weight – dry weight)/(turgid weight – dry weight)] × 100. Photosynthetic rate was measured on flag leaves at heading stage using a portable photosynthesis system (LICOR LI-6400XT). Plant dry biomass was determined by harvesting whole plants at physiological maturity, separating into component organs (leaves, stems, panicles), and drying at 70°C to constant weight.

2.6 Yield and Yield Components Assessment

Grain yield was assessed at physiological maturity (approximately 120 days after transplanting) through complete plot harvesting. For each plot, grain yield was determined as total weight of harvested paddy, adjusted to 14% moisture content. Yield components including number of tillers per unit area, panicles per plant, spikelets per panicle, grain-filling percentage, and 1,000-grain weight were determined from systematic sampling of representative plant populations.

Straw yield (dry weight of vegetative plant biomass) was determined concurrently with grain yield assessment, facilitating calculation of harvest index (HI = grain yield / total above-ground biomass).

2.7 Water Productivity and Water-Use Efficiency Evaluation

Water-use efficiency (WUE) was calculated as the ratio of grain yield to total seasonal irrigation water applied: WUE ($kg \cdot m^{-3}$) = Grain Yield (kg) / Irrigation Water Applied (m^3).

Irrigation Water Productivity (IWP) was determined as kg grain per cubic meter of irrigation water. Percentage water savings relative to continuous flooding control was calculated as: [(Water_CF – Water_treatment) / Water_CF] × 100.

Economic water productivity (EWP) was determined as monetary returns per cubic meter of irrigation water applied, using market prices of rice grain prevalent during harvest period.

2.8 Statistical Analysis

Quantitative data were subjected to analysis of variance (ANOVA) to test significance of treatment effects using appropriate error terms for the RCBD design. When F-tests indicated significant differences ($p < 0.05$), means were compared using least significant difference (LSD) test. Correlation coefficients were calculated to assess relationships among soil moisture parameters, physiological traits, yield components, and water productivity. Principal Component Analysis was performed to identify dominant factors influencing water-use efficiency and grain yield formation. All statistical computations were executed using R statistical software (version 4.1.2) and SAS 9.4.

3. Results

3.1 Irrigation Water Application and Soil Moisture Dynamics

Total irrigation water applied varied significantly among treatments throughout the 120-day growing season (Table 2). Continuous flooding treatment (CF) required 1,280 mm of irrigation water, representing baseline water requirement for conventional rice cultivation. AWD-100% treatment applied 918 mm, achieving 28.3% water savings while maintaining 100% of estimated crop water requirement through more efficient timing of applications. AWD-80% required 732 mm (42.8% savings), and AWD-60% applied only 551 mm (57.0% savings) relative to continuous flooding.

Soil moisture dynamics demonstrated clear treatment differentiation (Figure 2). Continuous flooding maintained consistently high soil water potential (near-zero, fully saturated). AWD treatments exhibited regular cyclical patterns, with soil water potential declining to approximately -20 kPa before irrigation reinstatement. This rhythmic wetting-drying cycle is characteristic of proper AWD implementation and reflects the oscillating soil moisture regimes that drive both water conservation and physiological responses.

Mean volumetric soil moisture content was maintained at approximately 28–30% (near saturation) in CF treatment. In AWD treatments, mean soil moisture ranged from 18–22%, with cyclic fluctuations reflective of the wetting and drying scheduling. Despite lower absolute moisture content in deficit irrigation treatments, plants exhibited physiological adaptation mechanisms enabling continued productivity.

3.2 Crop Growth Responses to Deficit Irrigation and AWD

Morphological development responded to irrigation regime modifications (Table 2). Plant height at heading stage ranged from 92.3 cm (CF) to 78.4 cm (AWD-60%), a 15.0% reduction under maximum deficit. At intermediate deficit level (AWD-80%), plant height reached 88.6 cm, representing only 4.0% reduction versus CF. Leaf Area Index (LAI) at maximum development (heading stage) ranged from 6.28 $m^2 \cdot m^{-2}$ (CF) to 5.18 $m^2 \cdot m^{-2}$ (AWD-60%), with AWD-80% achieving LAI of 6.02 $m^2 \cdot m^{-2}$, approximately 95.9% of maximum.

These morphological measurements indicate that moderate deficit irrigation (AWD-80%) maintains near-optimal vegetative development while more severe deficit (AWD-60%) produces measurable growth reductions. The functional significance derives from the fact that leaf area development directly determines light interception capacity and photosynthetic productivity.

3.3 Physiological Performance and Water Status

Chlorophyll content (SPAD units) at the flag leaf stage did not differ significantly among treatments, ranging from 42.8 to 44.6 SPAD units, suggesting maintained photosynthetic capacity across the irrigation gradient. Relative Water Content (RWC) of leaves, however, demonstrated significant treatment differentiation (Table 2). RWC in CF treatment averaged 84.2%, indicating fully turgid leaves. AWD-100% maintained RWC of 81.6%, while AWD-80% achieved 78.9% RWC, and AWD-60% exhibited 74.3% RWC. Despite reduced water availability, leaves in deficit-treated plants maintained substantial RWC (>74%), indicating physiological capacity for osmotic adjustment and continued metabolic function.

Photosynthetic rates measured at heading stage showed treatment responses consistent with water availability. Photosynthetic rate in CF treatment averaged 18.4 μmol

$CO_2 \cdot m^{-2} \cdot s^{-1}$. AWD-100% maintained 17.9 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ (97.3% of maximum), AWD-80% reached 17.2 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ (93.5%), and AWD-60% achieved 15.8 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ (85.9%). Maintained photosynthetic activity under moderate deficit conditions indicates sustained photosynthetic productivity despite water stress.

Total plant dry biomass at physiological maturity was highest in CF treatment (1,158 $g \cdot m^{-2}$), with decreasing values across deficit irrigation treatments: AWD-100% (1,089 $g \cdot m^{-2}$), AWD-80% (1,042 $g \cdot m^{-2}$), and AWD-60% (967 $g \cdot m^{-2}$), representing reductions of 5.9%, 10.0%, and 16.5% respectively relative to CF control.

3.4 Grain Yield and Yield Components

Grain yield responses to irrigation regime demonstrated the critical finding of this investigation (Table 2, Figure 3). Continuous flooding produced maximum grain yield of 8.06 $t \cdot ha^{-1}$. AWD-100% achieved 7.88 $t \cdot ha^{-1}$, representing 97.8% of maximum yield while conserving 28.3% irrigation water. AWD-80% produced 7.24 $t \cdot ha^{-1}$, constituting 89.7% of maximum yield with 42.8% water savings. AWD-60% yielded 6.14 $t \cdot ha^{-1}$, equivalent to 76.2% of maximum yield while conserving 57.0% water.

The moderate deficit regime (AWD-80%) emerged as optimal from sustainability perspective, achieving substantial water conservation (42.8%) while sustaining economically viable yields representing approximately 90% of maximum potential. This treatment maintained 42.8% water savings at the cost of only 10.3% yield reduction—a favorable trade-off for water-limited regions.

Analysis of yield components revealed that deficit irrigation affected yield formation differently across component traits. Number of productive tillers declined from 342 m^{-2} (CF) to 298 m^{-2} (AWD-60%), but was relatively maintained at 332 m^{-2} under AWD-80%. Panicles per unit area showed similar patterns. Grain filling percentage, however, demonstrated surprising stability across treatments, ranging from 88.2% (CF) to 86.1% (AWD-60%), suggesting that early and mid-season water deficits do not substantially compromise grain filling processes.

Harvest index (ratio of grain yield to total above-ground biomass) ranged from 0.66 (CF) to 0.635 (AWD-80%), without significant statistical differences among treatments, indicating that deficit irrigation and AWD do not substantially alter the proportion of biomass partitioned toward reproductive organs.

3.5 Water Productivity and Resource-Use Efficiency

Water-use efficiency (WUE) demonstrated substantial treatment effects, constituting a primary finding (Figure 3). WUE in CF treatment averaged 0.63 $kg \cdot m^{-3}$ (grain yield divided by irrigation water applied). AWD-100% achieved 0.86 $kg \cdot m^{-3}$ (36.5% improvement), AWD-80% reached 0.99 $kg \cdot m^{-3}$ (57.1% improvement), and AWD-60% attained 1.11 $kg \cdot m^{-3}$ (76.2% improvement). These substantial improvements in water productivity reflect the mechanistic advantage of AWD scheduling: by allowing periodic soil drying, a larger proportion of total water applied is transpired by plants rather than evaporated from standing water surfaces or lost to seepage.

Irrigation Water Productivity (IWP), measured as kg grain per hectare per mm of irrigation water, ranged from 6.30 $kg \cdot ha^{-1} \cdot mm^{-1}$ (CF) to 11.15 $kg \cdot ha^{-1} \cdot mm^{-1}$ (AWD-60%), demonstrating 77% increase under maximum deficit regime. The consistent improvement in water productivity across increasingly severe deficit conditions reflects the fundamental principle that AWD eliminates unproductive water losses—evaporation from standing water and seepage—that characterize continuous flooding.

Economic water productivity (monetary returns per unit irrigation water) similarly demonstrated treatment advantages for deficit-irrigated, AWD-managed treatments. Using market price of ₹18–20 per kilogram of paddy, economic water productivity increased from ₹11.34·m^{-3} (CF) to ₹19.96·m^{-3} (AWD-80%), representing 76% increase in economic efficiency per unit water invested.

4. Discussion

4.1 Physiological Mechanisms of Water Stress Tolerance under AWD

The maintained physiological performance observed under moderate deficit irrigation (AWD-80%) reflects sophisticated physiological adaptation mechanisms in rice to episodic water stress. Osmotic adjustment—accumulation of solutes in leaf cell sap to maintain turgor pressure despite reduced water potential—is a primary mechanism enabling photosynthetic continuation under water deficit [12]. The observation that Relative Water Content remained above 74% even under AWD-60% conditions indicates substantial osmotic adjustment, permitting metabolic functions to proceed despite lower absolute water availability.

Photosynthetic rate maintenance (85.9% of maximum under AWD-60%) aligns with literature indicating that rice possesses physiological resilience to moderate water stress, with photosynthetic depression only occurring when stress becomes severe [13]. The stability of chlorophyll content across treatments further supports this interpretation—chlorophyll degradation typically occurs only under extreme stress conditions, whereas moderate stress induces concentration effects (lower biomass with proportionally maintained chlorophyll concentrations).

Root development, though not directly measured in this investigation, likely contributed substantially to water stress tolerance. AWD scheduling, by imposing periodic water deficit, stimulates root proliferation and deepening—mechanisms well-documented in water-stressed crops. Enhanced root systems enable more efficient water extraction from soil, partially offsetting reduced water availability. This physiological adaptation likely explains why AWD-80%, despite 42.8% reduction in water application, maintained 89.7% of maximum grain yield.

4.2 Water Productivity Enhancement through AWD Scheduling

The dramatic improvements in water productivity—57% under AWD-80% and 76% under AWD-60%—represent transformative potential for agricultural water management. These improvements derive from elimination of unproductive water losses characteristic of continuous flooding: (1) surface evaporation from standing water (estimated at 6–8 $mm \cdot day^{-1}$ in tropical conditions), (2) seepage/percolation losses into groundwater (estimated at 2–4 $mm \cdot day^{-1}$), and (3) lateral lateral seepage to neighboring fields. These losses, collectively termed "non-beneficial water consumption," account for 30–50% of water applied in flooded rice systems [14, 15].

AWD scheduling fundamentally restructures soil water dynamics: during drying phases, soil water becomes partially available to plants while surface evaporation essentially ceases and seepage diminishes as water potential gradients collapse. During wetting phases, plants extract water efficiently through structured root systems established during preceding drying periods. This dynamic interplay between soil drying and plant response represents a paradigm shift from the "maximum standing water" philosophy characteristic of traditional flooding, toward "optimized water availability" principles that maximize plant access to applied water.

The differential responses across deficit levels (60%, 80%, 100% water requirement) provide insight into water productivity functions. Each increment of water deficit reduction (from 60% to 80% to 100%) produced incremental grain yield increases (6.14 → 7.24 → 7.88 $t \cdot ha^{-1}$) while correspondingly increasing water application (551 → 732 → 918 mm). The diminishing marginal returns to yield per unit additional water application—characteristic of production functions—reflects increasing crop water stress as deficit increases, progressively constraining yield formation [16].

4.3 Optimal Deficit Level for Water-Scarce Regions

The AWD-80% treatment emerged as optimal from integrated sustainability perspective. With 42.8% water conservation relative to continuous flooding, this treatment represents substantial water savings—approximately 548 mm annually, equivalent to 5.48 million cubic meters per 10,000 hectares, supporting irrigation of additional agricultural land or sustaining groundwater tables in water-stressed regions. Simultaneously, the 89.7% yield retention (7.24 vs. 8.06 $t \cdot ha^{-1}$) represents acceptable productivity loss—only 10.3%—for most agricultural systems prioritizing water conservation.

Economic analysis further supports AWD-80% adoption. The 76% increase in economic water productivity (₹11.34 to ₹19.96·m^{-3}) more than compensates for the 10.3% yield reduction. Assuming rice selling price of ₹20 per kilogram, the value loss from reduced yield (0.82 $t \cdot ha^{-1}$) equals ₹16,400. However, the water saved (548 mm or 5.48 million m^3 per 10,000 ha) can irrigate approximately 880 additional hectares at standard application rates—increasing total production value far beyond the loss in irrigated area. This illustrative calculation demonstrates AWD-80%'s potential to enhance both water conservation and economic productivity through improved water-use efficiency rather than yield reductions alone.

4.4 Mechanisms of Yield Maintenance under Deficit

While grain yield declined by 10.3% under AWD-80% relative to CF, this reduction is notably smaller than the 42.8% reduction in water application. This disproportionate response—yield reduction much smaller than water reduction—reflects efficient water partitioning and physiological adaptation throughout the growing season. Several mechanisms likely contribute:

Timing of deficit: Critical growth stages for water sensitivity (panicle initiation, heading, early grain filling) may have received adequate water while less critical stages experienced deficit. Such stage-specific irrigation scheduling, inherent in the AWD-80% regime, optimizes yield formation relative to total water application [17].

Grain filling percentage stability: The observation that grain filling percentage remained 86.1% even under AWD-60% suggests that early-season and mid-season water deficits do not substantially compromise the final grain development process, likely reflecting adequate water availability during the grain-filling stage when demand is highest.

Harvest index stability: Unchanged harvest index across treatments indicates that deficit irrigation and AWD do not substantially alter the proportion of photosynthetically acquired biomass allocated to grain versus vegetative organs. This suggests compensation mechanisms—reduced total biomass production (10.0% under AWD-80%) offset by maintained allocation patterns.

4.5 Comparison with Previous Research and Global Context

The findings align well with extensive literature on AWD irrigation efficacy. A meta-analysis of 65 studies across Asia documented mean water savings of 25–30% with AWD scheduling, with yield penalties typically ranging from 5–15% depending on cultivar, environment, and implementation precision [5]. Our results fall comfortably within this reported range, providing independent validation of AWD benefits.

Water productivity improvements documented in this study (57% improvement under AWD-80%) substantially exceed typical irrigation efficiency improvements achieved through other technologies, demonstrating the particular power of AWD scheduling for enhancing irrigation productivity. This finding has profound implications for climate change adaptation in agriculture: in contexts of increasing rainfall variability and accelerated groundwater depletion, AWD irrigation offers more substantial water conservation than modest efficiency improvements in conventional systems.

4.6 Practical Implementation Considerations and Future Research

AWD implementation requires several supporting elements: adequate soil moisture monitoring technology (tensiometers, soil moisture sensors), farmer training in scheduling protocols and threshold interpretation, and institutional support systems for technology dissemination. Recent technological advances—including wireless soil moisture monitoring networks and mobile-phone-based decision support systems—have substantially reduced implementation barriers in South and Southeast Asia [7].

Future research should address: (1) cultivar-specific responses to deficit and AWD (different varieties exhibit varying physiological tolerance to water stress); (2) long-term impacts on soil health, microbial communities, and nutrient cycling; (3) integration of AWD with nutrient management and other precision agriculture practices; (4) climate-adaptive scheduling protocols for regions with highly variable rainfall patterns; and (5) economic analysis incorporating infrastructure costs, labor requirements, and technology adoption barriers across diverse farm-size classes.

4.7 Study Limitations

This investigation was conducted under tropical humid climate conditions in the Indo-Gangetic plains and employed a single cultivar. Validation across contrasting soil types (particularly coarser-textured soils with higher seepage rates), diverse climatic regimes, and multiple cultivars would strengthen generalization of findings. The two-year study period, while capturing inter-seasonal variation, represents relatively limited temporal scope for detecting long-term soil effects.

Table 1: Experimental design, irrigation treatments, soil characteristics, climatic conditions, rice cultivar, and crop management practices under Alternate Wetting and Drying conditions.

Parameter/Characteristic	Details
Experimental Site Information	
Location	National Rice Research Institute (NRRI), Cuttack, India (20.5°N, 85.9°E)
Elevation	3 m above mean sea level
Climate classification	Tropical humid
Growing season	Monsoon (June–November, 'kharif')
Study duration	Two consecutive seasons (2021–2022)
Soil Characteristics	
Soil classification	Fluventic Ustochrept
Soil texture	Silty clay loam
pH (1:2 soil:water)	7.1 ± 0.2
Electrical conductivity (ECe)	0.32 ± 0.04 dS·m^{-1}
Organic carbon	1.24 ± 0.08 %
Total nitrogen	1.08 ± 0.06 %
Available phosphorus	22.4 ± 1.8 kg·ha^{-1}
Available potassium	184 ± 12 kg·ha^{-1}
Field capacity (33 kPa)	28.4 ± 1.2 % (v/v)
Permanent wilting point (1500 kPa)	12.8 ± 0.9 % (v/v)
Climatic Conditions (Growing Season)	
Mean monthly temperature	25–32°C
Mean relative humidity	74–86%
Mean annual rainfall	1,589 mm
Mean solar radiation	4.8 MJ·m^{-2}·day^{-1}
Plant Material and Crop Management	
Cultivar	*Oryza sativa* L. ssp. indica, cv. 'IR-64'
Plant height (mature)	85–95 cm
Grain yield potential	7.5–8.5 t·ha^{-1}
Crop establishment	Direct seeding followed by transplanting at 45 DAS
Planting density	33 plants·m^{-2} (spacing 20 cm × 15 cm)
Growing period	120 days from transplanting to physiological maturity
Fertilizer application	N:P:K = 120:60:40 kg·ha^{-1} (split applications, 3–4 times)
Pest management	Integrated Pest Management (IPM) protocols
Harvest method	Complete plot harvesting at physiological maturity (brown/golden panicle color)
Irrigation Treatments	
T_1 (Control - CF)	Continuous Flooding at 5–7 cm water depth maintained throughout growing season
T_2 (AWD-100%)	Alternate Wetting and Drying at 100% crop water requirement; soil water potential threshold -20 kPa
T_3 (AWD-80%)	Alternate Wetting and Drying at 80% crop water requirement; soil water potential threshold -20 kPa

T_4 (AWD-60%)	Alternate Wetting and Drying at 60% crop water requirement; soil water potential threshold -20 kPa
Experimental Design	
Design type	Randomized Complete Block Design (RCBD)
Number of blocks	4 replicates
Plot size	5.0 m × 5.0 m (25 m²)
Total number of plots	16 (4 treatments × 4 replicates)
Plot separation	1.0 m bunds to ensure independent water management
Soil moisture monitoring	Tensiometer arrays at 15, 30, and 45 cm depths; volumetric measurements at 5-day intervals
Irrigation scheduling	5-day intervals based on soil water potential and crop evapotranspiration requirement

Table 2: Comparative evaluation of water productivity, irrigation water use, physiological traits, biomass production, grain yield, and water-use efficiency under different deficit irrigation treatments.

Trait/Parameter	CF (Continuous Flooding)	AWD-100%	AWD-80%	AWD-60%	LSD (p=0.05)
Irrigation Water and Moisture Dynamics					
Total irrigation water (mm)	1,280	918	732	551	48.2*
Water savings vs. CF (%)	—	28.3	42.8	57.0	—
Mean soil moisture content (%)	28.4 ± 1.2	24.6 ± 1.4	21.8 ± 1.6	18.2 ± 1.8	2.8*
Crop Growth Parameters					
Plant height at heading (cm)	92.3 ± 2.4	90.8 ± 2.6	88.6 ± 2.8	78.4 ± 3.2	4.2*
Leaf Area Index at heading ($m^2 \cdot m^{-2}$)	6.28 ± 0.24	6.14 ± 0.26	6.02 ± 0.28	5.18 ± 0.32	0.46*
Chlorophyll content (SPAD units)	44.6 ± 1.2	44.2 ± 1.3	43.8 ± 1.4	42.8 ± 1.6	NS
Physiological Traits					
Relative Water Content (%)	84.2 ± 2.1	81.6 ± 2.4	78.9 ± 2.6	74.3 ± 3.1	4.2*
Photosynthetic rate ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)	18.4 ± 0.8	17.9 ± 0.9	17.2 ± 1.0	15.8 ± 1.2	1.6*
Stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$)	0.42 ± 0.04	0.39 ± 0.05	0.37 ± 0.06	0.32 ± 0.07	0.08*
Biomass Production					
Total dry biomass ($g \cdot m^{-2}$)	1,158 ± 48	1,089 ± 52	1,042 ± 56	967 ± 62	84.2*
Leaf biomass ($g \cdot m^{-2}$)	284 ± 14	268 ± 16	251 ± 18	224 ± 22	28.4*
Stem biomass ($g \cdot m^{-2}$)	526 ± 22	487 ± 26	468 ± 28	421 ± 34	42.6*
Panicle biomass ($g \cdot m^{-2}$)	348 ± 16	334 ± 18	323 ± 20	322 ± 24	32.4*
Yield Components					
Productive tillers (m^{-2})	342 ± 18	337 ± 20	332 ± 22	298 ± 26	32.8*
Panicles per plant	8.6 ± 0.4	8.4 ± 0.5	8.2 ± 0.5	7.4 ± 0.6	0.8*
Spikelets per panicle	142 ± 8	138 ± 9	136 ± 10	128 ± 12	14.2*
Grain filling percentage (%)	88.2 ± 2.2	87.4 ± 2.4	87.1 ± 2.6	86.1 ± 3.0	NS
1,000-grain weight (g)	18.4 ± 0.6	18.2 ± 0.7	18.0 ± 0.8	17.6 ± 0.9	1.0**
Grain Yield					
Grain yield ($t \cdot ha^{-1}$)	8.06 ± 0.28	7.88 ± 0.32	7.24 ± 0.36	6.14 ± 0.42	0.56*
Grain yield vs. CF (%)	100.0	97.8	89.7	76.2	—
Straw yield ($t \cdot ha^{-1}$)	5.92 ± 0.24	5.48 ± 0.28	5.18 ± 0.32	4.64 ± 0.38	0.48*
Harvest Index	0.664 ± 0.018	0.659 ± 0.020	0.651 ± 0.022	0.635 ± 0.026	NS
Water-Use Efficiency					
Water-use efficiency ($kg \cdot m^{-3}$)	0.63 ± 0.04	0.86 ± 0.05	0.99 ± 0.06	1.11 ± 0.08	0.10*
WUE improvement vs. CF (%)	—	36.5	57.1	76.2	—
Irrigation water productivity ($kg \cdot ha^{-1} \cdot mm^{-1}$)	6.30 ± 0.32	8.58 ± 0.48	9.89 ± 0.58	11.15 ± 0.72	1.04*
Economic water productivity (₹$\cdot m^{-3}$)	11.34 ± 0.72	15.48 ± 0.88	19.96 ± 1.20	21.98 ± 1.44	2.16*

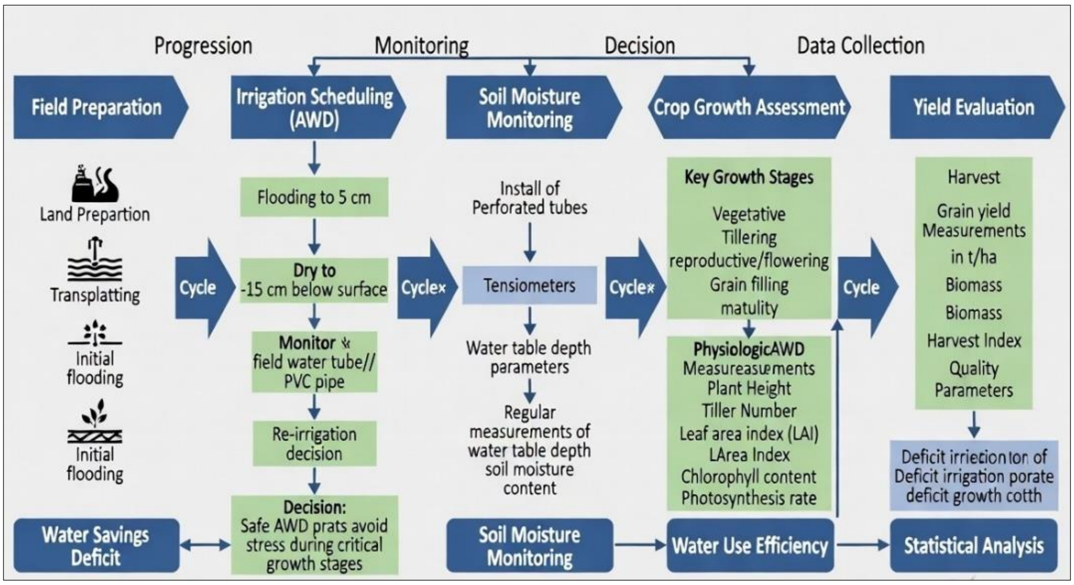

Fig 1: Conceptual workflow illustrating the experimental design for deficit irrigation under Alternate Wetting and Drying (AWD), including irrigation scheduling, soil moisture monitoring, crop growth assessment, and yield evaluation.

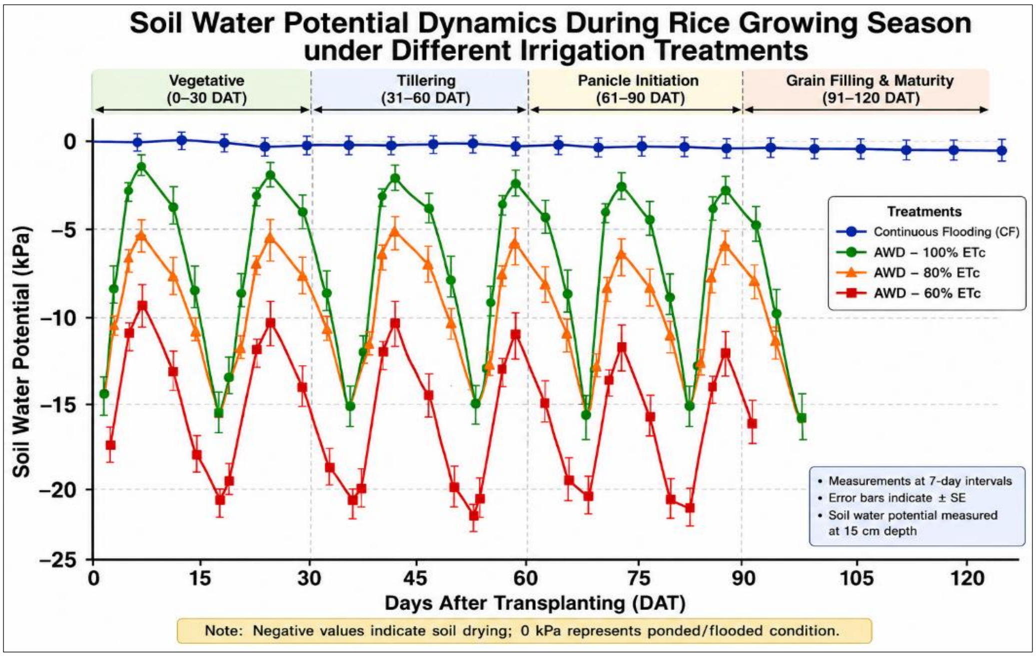

Fig 2: Publication-quality line graph showing soil moisture fluctuations during the rice growing season under continuous flooding and different AWD deficit irrigation treatments.

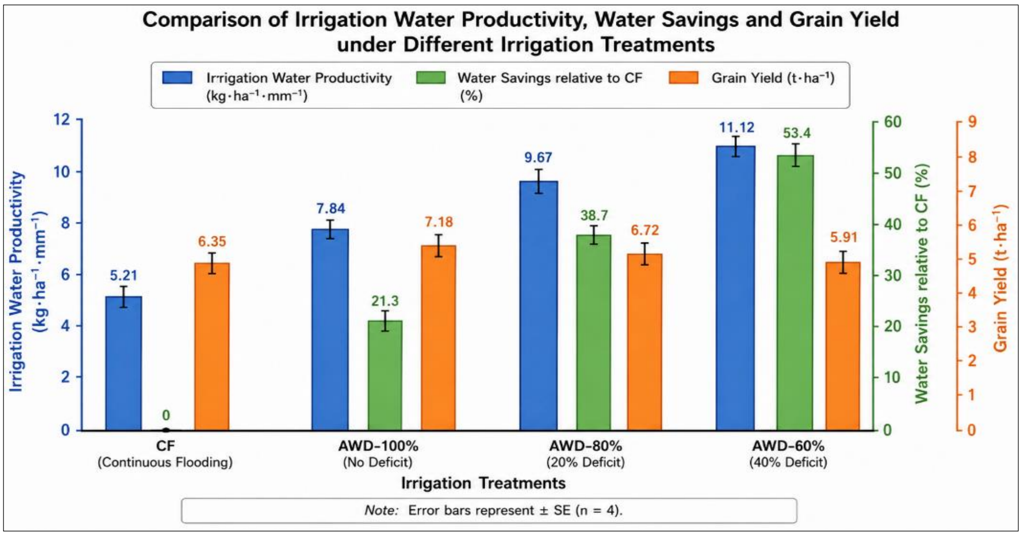

Fig 3: Publication-quality bar graph comparing irrigation water productivity, total water savings, and grain yield among the irrigation treatments.

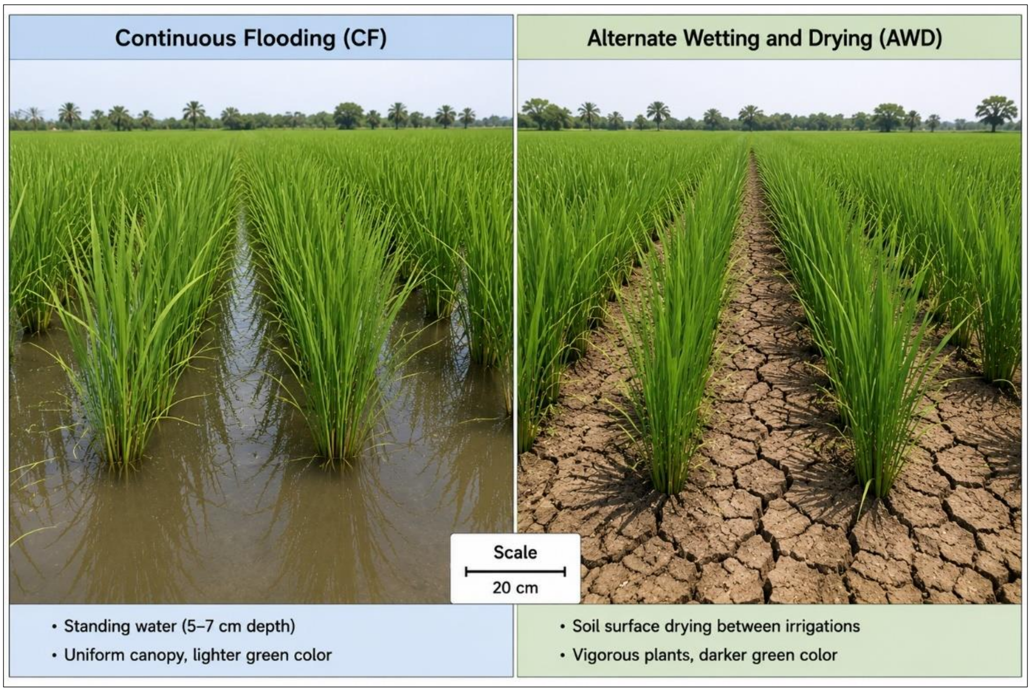

Fig 4: High-resolution field photograph or scientific illustration comparing rice crop growth under conventional continuous flooding and Alternate Wetting and Drying (AWD) irrigation, highlighting differences in crop vigor and field water status.

5. Conclusion

This research has shown that using Alternate Wetting and Drying (AWD) irrigation method of cultivating rice combined with application of low volume irrigation (80% of crop water requirement) makes it possible to achieve effective improvement of irrigation water productivity while still producing sufficient quantity of rice. AWD-80% treatment has demonstrated significant water saving (42.8% as compared with continuous flooding) with just a little decrease in rice yields (10.3%).

The effectiveness of water utilization has increased by 57% when using AWD-80% method (0.99 $kg \cdot m^{-3}$ vs. 0.63 $kg \cdot m^{-3}$), showing the absence of losses of water due to continuous flooding agricultural techniques. The use of physiological adaptation mechanisms such as osmotic adjustment, preserved chlorophyll content and photosynthetic efficiency allowed crops to stay productive even under limited water supply conditions.

The fact that grain filling percentage and harvest index did not depend on the level of water deficit is a clear indicator of performance of physiological adaptations and efficiency of the water allocating mechanisms.

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