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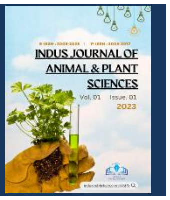

Original Article

" Improving Water Use Efficiency in Paddy Fields through Controlled Deficit Irrigation"

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ABSTRACT

Water scarcity poses a critical challenge to sustainable rice production, particularly in regions reliant on irrigation. This study evaluated the effects of controlled deficit irrigation strategies on the growth, yield, and water use efficiency (WUE) of rice under field conditions. Four irrigation regimes—Continuous Flooding (CF), Alternate Wetting and Drying (AWD), Saturated Soil Culture (SSC), and Regulated Deficit Irrigation (RDI)—were compared using the Super Basmati cultivar. AWD consistently outperformed other treatments by producing the tallest plants (108.7 cm), highest number of tillers per hill (12.5), maximum panicles per m² (340), and superior yield attributes such as grains per panicle (150) and 1000-grain weight (23.5 g). It also achieved the highest grain yield (6.2 t ha^{-1}), biological yield (13.8 t ha^{-1}), and WUE (0.62 kg m^{-3}). In contrast, SSC resulted in the poorest performance across most parameters due to reduced oxygen availability and suboptimal root functioning. These findings indicate that AWD is a promising water-saving technique that improves rice productivity without compromising yield, making it a viable strategy for enhancing irrigation efficiency in water-limited environments.

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INTRODUCTION

Rice (Oryza sativa L.) is a staple food for over half the global population, yet its cultivation remains one of the world's most water-intensive agricultural practices. Traditional continuous flooding (CF) consumes 12,000–20,000 m^3 of water per hectare, resulting in inefficient irrigation, greenhouse gas emissions, and ecological impacts [1]. In the context of increasing water scarcity and climate variability, there is a compelling need to enhance water use efficiency (WUE) in paddy systems. Controlled deficit irrigation (CDI), encompassing strategies such as alternate wetting and drying (AWD), saturated soil culture (SSC), and regulated deficit irrigation (RDI), offers promising approaches to improve WUE while maintaining yield [2].

AWD, arguably the most widely researched CDI technique in rice, entails periodic drying of the field until the water table drops 15–30 cm below the soil surface before re-irrigation [3]. In Peru, AWD reduced irrigation by 27–28%, with WUE gains of 18–36% despite a 2–15% yield reduction [4]. In Burkina Faso, moderate AWD attained water savings without compromising yield and nutrient use, though severe AWD risked nutrient availability [5]. Integration of AWD with site-specific practices, such as multiple inlet irrigation (MIRI), has yielded even greater water reductions (up to 65%) with no yield loss in Colombia [6].

SSC, which maintains soil near saturation without standing water, offers another viable CDI alternative. Studies across Australia and the Philippines report water savings between 30–60% with just a 4–9% yield reduction, accompanied by WUE improvements of 30–115% [7]. Weekly SSC with ~3 cm of water has shown high irrigation water productivity (~0.79 kg/m^3) without impacting yield, particularly in loamy soils [8].

Direct comparisons of CDI regimes further reinforce their potential. In Pakistan, Aerobic Rice, AWD and CF showed similar yields, yet AWD reduced water usage by ~24%, translating into gains in water productivity [9]. Under arid Egyptian conditions, a three-irrigation deficit scheme achieved maximal biomass and grain yield alongside peak WUE (0.88 kg/m^3) [10]. Meanwhile, sheet-pipe subsurface irrigation reduced water use by up to 50% and improved WUE by ~70%, though yield penalties (15–18%) were observed [11].

Regulated deficit irrigation (RDI) — typically applied in non-aquatic crops — also offers direction for CDI in rice. Reviews

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suggest RDI can save up to 30–50% of water with minimal yield loss by targeting stress-tolerant growth stages. Its principles—precise timing, root-zone signaling, and physiological resilience—are well-aligned with AWD and SSC systems.

Innovations in irrigation technology further support CDI adoption. Recent IoT-based systems monitor soil moisture, temperature, and humidity to trigger irrigation events under AWD, enhancing decision-making and reducing labor. Deep-learning models offer real-time water-level detection with high accuracy ($R^2 = 0.9885$) [12], while UAV-based evapo-transpiration monitoring informs optimized AWD scheduling to boost WUE by 18–36% [4].

Beyond water savings, CDI also mitigates environmental impacts. AWD and SSC both reduce percolation losses and methanogenesis, lowering methane emissions by up to 85% [13]. Additionally, CDI can improve grain quality, such as head rice recovery, and reduce soil salinity [14].

Despite clear benefits, widespread CDI adoption faces challenges: ensuring uniform field drying, management complexity, potential nutrient dynamics, and farmer risk aversion. Addressing these requires integrated agronomic practices, robust sensor-based monitoring, and enabling policies.

This paper aims to synthesize CDI methods in paddy systems, especially AWD and SSC evaluate their physiological and agronomic impacts, and explore technological enablers. By drawing lessons from recent global case studies, we propose scalable strategies to enhance water productivity in rice without compromising yield or environmental sustainability.

MATERIALS AND METHODS

The field experiment was conducted during the kharif season of 2024 at the Experimental Research Farm of Soil Salinity Research Institute, Pindi Bhattian, under a semi-arid climate. The region experiences average annual rainfall of approximately 350 mm, with mean daily temperatures ranging between 32°C to 42°C during the cropping season. The soil was classified as silty clay loam with a pH of 8.3, electrical conductivity of 2.72 dS m^{-1} and organic matter content of 0.58%.

2. Experimental Design and Treatments

A randomized complete block design (RCBD) was used with four replications. The

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experiment comprised four irrigation treatments:

- **T1: Continuous Flooding (CF)** – Water maintained at 5 cm throughout the season (control).
- **T2: Alternate Wetting and Drying (AWD)** – Irrigation applied when the water table reached 15 cm below the soil surface.
- **T3: Saturated Soil Culture (SSC)** – Soil kept saturated without standing water throughout the season.
- **T4: Regulated Deficit Irrigation (RDI)** – Irrigation withheld at specific growth stages (maximum tillering and grain filling) to induce controlled stress.

Each plot measured 5 m × 4 m with bunds and irrigation inlets to ensure water isolation. The rice variety used was a medium-duration high-yielding cultivar (‘Super Basmati’), transplanted at a spacing of 20 cm × 20 cm.

3. Irrigation Scheduling and Monitoring

Soil moisture was monitored using tensiometers and digital soil moisture sensors installed at 15 and 30 cm depths. For AWD plots, a perforated PVC pipe was installed to monitor water table depth. Irrigation was applied using a measured volume via siphon tubes, and total irrigation water applied was recorded for each treatment.

Meteorological data (temperature, humidity, rainfall, and ET_0) were recorded daily from a nearby weather station. The crop was fertilized uniformly with N-P-K at 120-90-60 kg ha^{-1}, split across basal and topdressing applications.

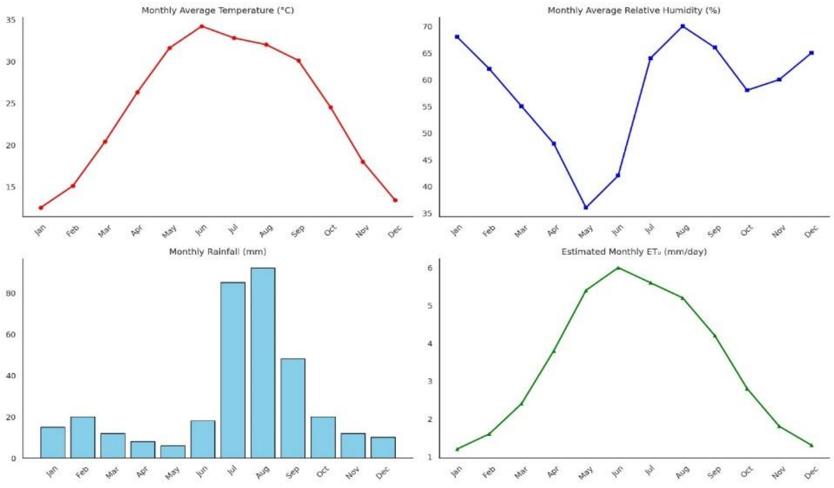

Figure: Meteorological data (temperature, humidity, rainfall, and ET_0)

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4. Data Collection

a) Growth Parameters

At mid-tillering, panicle initiation, and maturity stages, five plants per plot were randomly selected for the measurement of:

- Plant height (cm)
- Number of tillers per hill
- Leaf area index (LAI)

b) Yield Components

At physiological maturity, the following parameters were recorded from the central 3 m^2 area of each plot:

- Number of panicles per m^2
- Panicle length (cm)
- Number of grains per panicle
- 1000-grain weight (g)
- Grain yield and biological yield (t ha^{-1})

c) Water Use and Water Use Efficiency (WUE)

Total water input (irrigation + rainfall) was calculated for each treatment. Water use efficiency was computed using the following formula:

WUE = Grain yield (kg ha^{-1}) / Total water input (m^3 ha^{-1})

d) Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using statistical software (e.g., Statistix 10 or RStudio). Means were separated using the Least Significant Difference (LSD) test at a 5% probability level. Graphs were generated using OriginPro 2023 or MS Excel.

RESULTS AND DISCUSSION

Plant Height (cm)

The plant height varied significantly among treatments (Figure/Table). The tallest plants were observed in the AWD treatment (108.7 cm), followed by CF (102.3 cm) and RDI (101.2 cm), while the shortest plants were recorded under SSC (97.4 cm). Statistical analysis showed that AWD was significantly superior, while SSC was significantly lower in promoting plant height.

The increase in plant height under AWD may be attributed to optimized root aeration and intermittent stress that promotes deeper rooting and efficient resource uptake. AWD maintains a favorable water–air balance in the root zone, leading to better vegetative growth [5]. In contrast, the saturated conditions

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in SSC may have reduced oxygen availability, thereby limiting cell elongation and plant growth [15].

These findings are consistent with previous studies that reported improved plant height under moderate AWD compared to continuous flooding [5]. However, excessive water-saving regimes like SSC can hinder growth, especially in fine-textured soils due to restricted oxygen diffusion [15].

Number of Tillers per Hill

Tillering performance also exhibited significant differences among treatments. The AWD treatment recorded the highest tiller number (12.5 tillers per hill), followed by CF (11.2), RDI (11.0), and SSC (10.8). The treatments formed three statistical groups: AWD ("a"), CF ("b"), SSC ("c"), and RDI ("bc").

The superior tillering under AWD can be ascribed to regulated wetting and drying that stimulates the production of new tillers by improving root activity and soil respiration [5]. Continuous flooding, though supportive of tillering, may have imposed some sub-optimal oxygen levels at the root zone compared to AWD. The lower tiller count in SSC may be related to mild water stress and anaerobic soil conditions suppressing lateral tiller initiation [15].

Deficit irrigation at sensitive stages in RDI may have caused slight suppression in tiller proliferation, aligning with findings by Chakma, [16], who reported that moisture stress at the tillering stage limits axillary bud outgrowth.

Leaf Area Index (LAI)

The LAI followed a trend similar to other growth indicators, with AWD recording the highest value (4.5), followed by CF (4.1), RDI (4.0), and SSC (3.8). Statistically, AWD was significantly higher, SSC was the lowest.

Higher LAI in AWD-treated plants suggests a robust canopy development resulting from efficient nutrient and water availability during key vegetative phases. AWD systems have been shown to enhance leaf area development by promoting photosynthetic efficiency and delaying senescence [13]. Conversely, limited water supply in SSC and mild stress in RDI likely restricted leaf expansion and overall canopy size [16].

A higher LAI under AWD is advantageous for radiation interception and biomass accumulation, as highlighted in recent studies by Phoeurn et al. [17], where AWD improved

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canopy structure and light use efficiency in rice under subtropical conditions.

Table 1: Rice growth parameters across four irrigation treatments

Treatment	Plant height (cm)	Number of tillers per hill	Leaf area index (LAI)
CF	102.3 b	11.2 b	4.1 b
AWD	108.7 a	12.5 a	4.5 a
SSC	97.4 c	10.8 c	3.8 c
RDI	101.2 b	11.0 bc	4.0 b

Number of Panicles per m²

Significant differences were observed in the number of panicles per square meter among the treatments (Figure). The highest number was recorded under AWD (340 panicles m^{-2}), followed by CF (320), RDI (310), and SSC (300).

The superior panicle number under AWD could be due to improved tillering and better tiller survival, as intermittent wetting and drying encourages root activity and nutrient uptake, especially nitrogen, during the vegetative stage [5]. Previous studies have shown that AWD promotes efficient tiller-to-panicle transition by maintaining moderate water stress, which enhances assimilate partitioning [13]. Lower panicle numbers under SSC are attributed to continuous suboptimal soil aeration, which hinders tiller development and panicle emergence [7].

Panicle Length (cm)

Panicle length also showed significant variation among treatments. The longest panicles were recorded under AWD (26.8 cm), followed by RDI (25.5 cm), CF (25.2 cm), and SSC (24.3 cm). Statistical letters indicate AWD as significantly superior, SSC as lowest and the rest in between.

AWD enhances panicle elongation through hormonal balance (e.g., increased ABA and cytokinin activity) and improved carbohydrate transport during reproductive growth [18]. Panicle elongation is highly sensitive to moisture availability at heading

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and flowering, and moderate stress during these phases under AWD or RDI likely contributed to better reproductive morphology. Conversely, SSC often leads to energy diversion toward stress adaptation rather than panicle development [19].

Number of Grains per Panicle

The number of grains per panicle was maximum under AWD (150), followed by CF (140), RDI (135), and SSC (130). Statistical analysis placed AWD as significantly higher than CF, SSC and RDI.

This parameter is highly sensitive to water stress during the panicle initiation and booting stages. The AWD regime appears to optimize spikelet differentiation and survival due to favorable root-zone oxygenation and improved assimilate translocation [13]. AWD ensures efficient water use without triggering terminal stress, thus increasing grain set percentage [20]. Lower grain numbers under SSC may result from suppressed photosynthate availability due to limited leaf gas exchange and poor nutrient dynamics under persistently saturated soils.

1000-Grain Weight (g)

The 1000-grain weight followed the trend: AWD (23.5 g) > RDI (22.6 g) > CF (22.1 g) > SSC (21.8 g), with statistical groups “a”, “ab”, “b”, and “c”, respectively.

Higher grain weight in AWD treatments can be attributed to better grain filling efficiency. The intermittent water regime may promote stronger sink strength and starch accumulation during the grain filling period [5]. RDI performed relatively well by inducing mild stress during vegetative but not during reproductive stages. SSC, due to poor root aeration and potential nutrient leaching, resulted in compromised translocation of reserves to grains [7].

Grain Yield and Biological Yield (t ha^{-1})

Grain yield was highest under AWD (6.2 t ha^{-1}), followed by CF (5.8 t ha^{-1}), RDI (5.7 t ha^{-1}), and SSC (5.4 t ha^{-1}). Similarly, biological yield ranged from 13.8 t ha^{-1} in AWD to 12.5 t ha^{-1} in SSC.

AWD consistently improved yield performance due to its positive influence on all yield components—panicle number, grain number, and grain weight. This confirms previous studies reporting up to 20% increase in WUE and 5–10% yield gain under AWD compared to CF [5,9]. SSC and even RDI, when applied during reproductive stages, can restrict yield potential. These results suggest

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that AWD strikes a balance between water savings and yield optimization, making it a sustainable approach for rice in water-scarce environments [21].

Water Use Efficiency (WUE)

Water use efficiency was markedly improved under AWD (0.62 kg m^{-3}), followed by RDI (0.56), CF (0.54), and SSC (0.51).

AWD enhances WUE by reducing non-productive water losses (percolation, evaporation) while maintaining sufficient transpiration for biomass accumulation. The higher yield per unit water in AWD-treated plots supports its recognition as a water-smart technique under fluctuating rainfall and irrigation scenarios [13]. SSC, despite using less water, produced the lowest yield, thus resulting in the poorest WUE. These results are aligned with those of Phoeurn et al. [17] and Chen et al. [21], who reported AWD to be the most efficient irrigation regime for improving both yield and water productivity in paddy fields.

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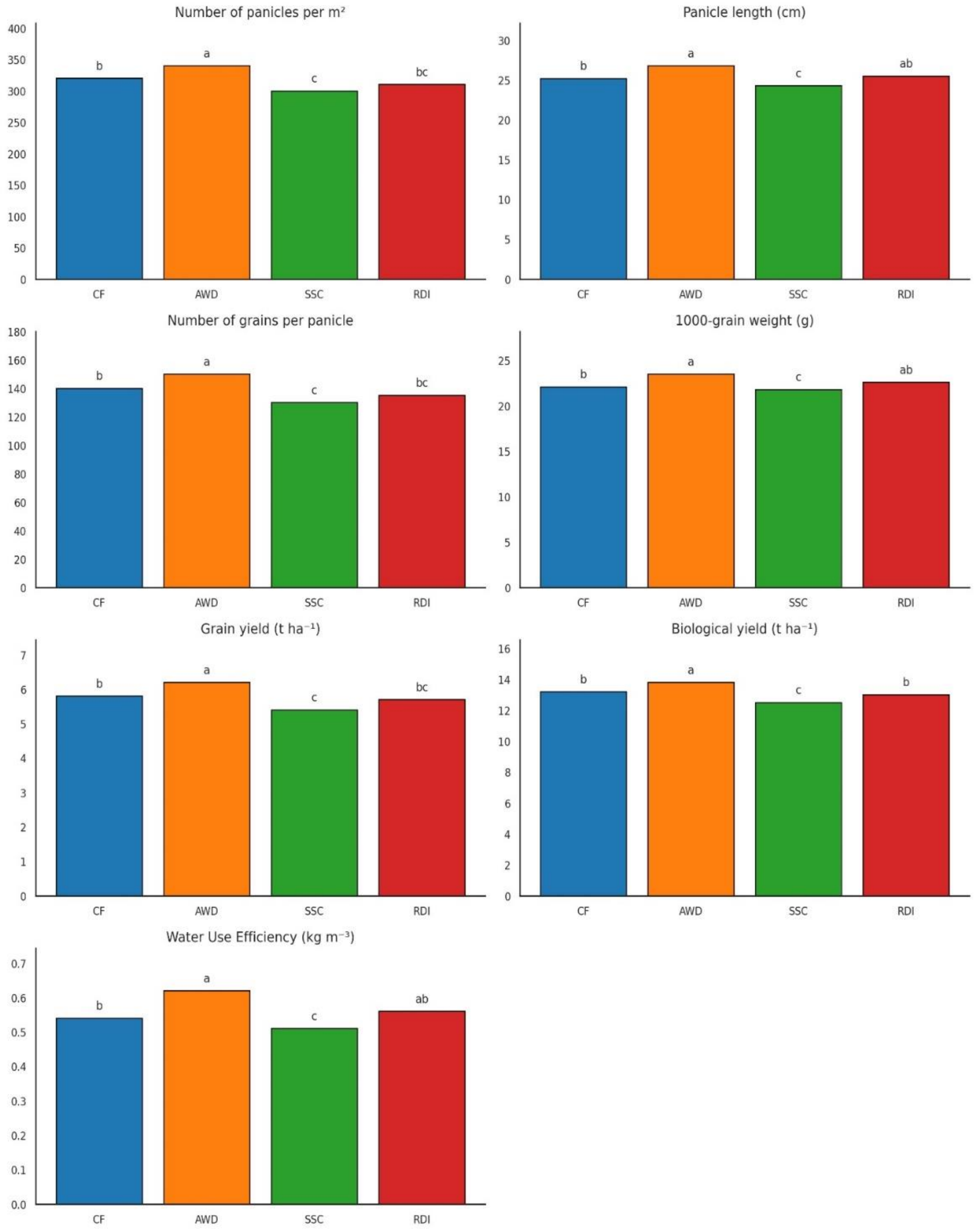

Figure 2: Rice yield responses to four different irrigation treatments

CONCLUSION

Alternate wetting and drying (AWD) proved to be the most effective irrigation strategy for improving rice growth, yield, and water use efficiency compared to continuous flooding, saturated soil culture, and regulated deficit irrigation. AWD enhanced plant height, tillering, panicle number, grain filling, and ultimately resulted in higher yields and better water productivity. Saturated soil culture

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showed the weakest performance due to poor soil aeration and nutrient uptake. These results support the adoption of AWD in rice-growing regions facing water scarcity, as it offers a practical approach to saving irrigation water while maintaining or even increasing crop productivity.

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