

An Assessment of the Feasibility and Impacts of Optimized Alternate Wetting and Drying (AWD) Systems in Various Thai Rice Cultivars

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Abstract

By assessing water-use efficiency in the face of increasing environmental uncertainties, this study addressed an essential requirement for climate adaptation in rice production. In two different seasons, we examined the physiological reactions of four Thai rice cultivars (RD61, RD97, RD111, and PTT1) under four different irrigation regimes: continuously flooding (CF), conventional AWD (cAWD), intensive AWD (iAWD), and drought condition (D). The results demonstrated that cAWD maintained grain yields and physiological integrity comparable to CF, with yield potential reaching 1.1 ton in the wet season. Conversely, iAWD and drought treatments induced severe metabolic strain, particularly in the dry season, where high VPD_{leaf} and lower humidity suppressed quantum yield of photosystem II (Φ_{PSII}) which decreased to 0.228–0.477, and electron transport rate (ETR) which decreased to 146–276 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Furthermore, restricted stomatal conductance (g_{sw}) under iAWD and drought treatments led to elevated leaf temperatures (T_{leaf}) and increased chlorophyll fluorescence (F_s). These comparisons highlight that while cAWD is a robust strategy, exceeding the -15 cm threshold poses significant risks to productivity. Seasonal dynamics significantly influenced genotypic responses to water management. During the wet season, characterized by higher rainfall and more frequent rainy days, RD61, RD97, and PTT1 demonstrated high adaptability under iAWD, maintaining grain yields comparable to the CF. Conversely, in the dry season under reduced rainfall and fewer rainy days, only RD61 managed with iAWD exhibited physiological resilience, sustaining a grain yield that did not statistically differ from CF. Therefore, the successful adaptation of alternative irrigation technique requires integrating

precise hydrological thresholds with cultivar-specific resilience and real-time climate data to ensure food security within the Water-Energy-Food Nexus.

Keywords: rice cultivation, alternative irrigation, alternate wetting and drying

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Introduction

Rice (*Oryza sativa* L.) is one of the most extensively cultivated and consumed crops globally, playing a vital role in food security, particularly among low-income populations. It serves as the primary dietary component for a great number of people worldwide than any other crops. Asia dominates both rice production and consumption, accounting for over 90% of global totals. Rice is cultivated in more than 100 countries, underscoring its critical importance in global agricultural systems. In the past decade, the area of rice cultivation has continuously increased to exceed 165 million hectares worldwide (Dawe et al., 2010; Rehman et al., 2022 Yen and Nam, 2025). Due to its high-water requirements, rice farming is extremely resource intensive. Over 780 billion cubic meters of water are used each year to support rice production worldwide. Compared to other cereal crops like maize or wheat, which typically use less than 1 m³ of water per kilogram of grain, this method uses roughly 1 to 3 m³ of water to produce just 1 kg of rice (Laphatphakhanut et al., 2021; Xie et al., 2025).

Global rice production faces the dual challenge of securing food security and adapting to severe water scarcity caused by climate change

(Arunrat, et al., 2020; Dadrasi et al., 2025). Due to climate change include temperature, solar radiation, atmospheric CO₂ concentration, precipitation and water availability, all of which have a significant impact on plant metabolism (Anwar et al., 2013; Malhi et al., 2021). This emphasizes how urgently rice agriculture has to embrace more sustainable water management techniques and increase irrigation efficiency. However, traditional continuous flooding in tropical rice paddies requires significant irrigation and is a major source of anthropogenic methane emissions (Wichaidist et al., 2023; Wichaidist et al., 2025a). To enhance the Water-Energy-Food nexus, alternative irrigation has emerged as an essential water-saving strategy.

Alternative irrigation techniques in rice cultivation, especially alternate wetting and drying (AWD), have shown potential to reduce methane emissions, a strong greenhouse gas commonly associated with conventional flooded rice systems, while also sustaining water resources. By addressing both water constraint and greenhouse gas reduction in the production of rice, these solutions provide a twofold benefit. However, the enhancement of alternative irrigation in rice is a process that need to be carefully evaluated, because rice is a crop that is susceptible to water

scarcity, which is also recognized as a semi-aquatic crop (Muthayya et al., 2014; Wichaidist et al., 2023). In a recent study, we discovered no noticeable effect on a number of physiological indicators (Wichaidist et al., 2025a). Therefore, using plant physiological data for managing water in rice fields is still an opportunity in water-saving techniques. In order to assist with decision-making concerning the efficiency of water use in alternative irrigation, this investigation intends to explore various physiological features that are associated to water status in plants with fluctuations in the AWD water level.

Materials and Methods

Treatments and Environmental Conditions

The field experiments were conducted at the Chainat Rice Research Center, situated in Mueang District, Chai Nat Province, Thailand. To ensure the reliability of the comparative data, all plots were managed under uniform agronomic practices, including standardized fertilization schedules and integrated pest management (IPM) protocols (Soil Science Division, 2000; Rice Research and Development Division, 2019), thereby isolating the effects of water management and cultivar genetics. Four cultivars of rice (*Oryza sativa* L.) - RD61, RD97, RD111, and PTT1 - were utilized in this study. The field experiment was laid out as a split-plot in randomized complete block design (RCBD) with four replications. Water management treatments were assigned to the main plots, while 4 cultivars as described above were allocated to

the subplots. The size of each individual subplot (experimental unit) was 6×6 m (36 m²). The four water management treatments evaluated in this study were designated as follows:

- a) Continuously Flooding (CF): Serving as the control group and the conventional irrigation baseline, this treatment maintained a steady water level to reflect standard lowland rice cultivation.
- b) Conventional Alternate Wetting and Drying (cAWD): A moderate water-saving regime where re-irrigation was triggered only when the perched water table dropped to 15 cm below the soil surface.
- c) Intensive Alternate Wetting and Drying (iAWD): A more intensive stress regime designed to test the limits of cultivar resilience, with a re-irrigation threshold of 30 cm below the soil surface.
- d) Drought (D): A second control group subjected to severe moisture depletion toward the reproductive stage, utilized to assess the physiological and yield-based performance under critical water scarcity.

Meteorological data were continually observed and recorded at the experimental site using an in-field weather station to provide a comprehensive overview of the environmental stressors and growth circumstances during the experimental periods. The data characterized two distinct cultivation seasons, hereafter referred to as the wet season (April – August 2025) and the dry season (October 2025 – February 2026), which

exhibited notable variations in solar radiation, hydrothermal patterns, and precipitation. The intensity of solar radiation, specifically within the 420 – 675 nm wavelength range closely aligning with the photosynthetically active radiation (PAR) spectrum was a critical factor in evaluating rice metabolic performance. In the wet season, the maximum light intensity reached 1338 W/m², with a diurnal mean of 422 W/m². In contrast, the dry season exhibited slightly lower radiation levels, with a peak intensity of 1135 W/m² and a daytime average of 362 W/m². The thermal environment differed significantly between the two seasons. The wet season was characterized by higher overall temperatures, peaking at 38.26°C with a mean of 30.23°C, creating a high-evaporative demand environment. The dry season presented a broader thermal range, with a maximum of 35.9°C and a significantly lower minimum of 15.0°C (mean of 25.6°C). Relative humidity (RH) remained consistently high in both seasons, peaking near saturation (98.8% to 99.6%). Rainfall patterns during the study periods provided the natural hydrological backdrop for the AWD irrigation treatments. The wet season recorded 37 rainy days, with a maximum daily precipitation of 41.2 mm. While the dry season had fewer rainy days (26 days), it experienced higher-intensity individual events, with daily rainfall peaking at 63.0 mm.

Assessment of Photosynthetic Characteristics

To evaluate the photosynthetic efficiency and physiological responses were systematically recorded using a portable porometer/fluorometer

(LI-600, LI-COR Biosciences, Lincoln, NE, USA). All measurements were performed during the peak metabolic period of 09:00–11:00 AM to ensure maximum photosynthetic activity and consistency across treatments (Wichaidist et al., 2025b). For each experimental plot, five fully expanded flag leaves were randomly selected from individual hills (excluding border rows) for the measurements. The study assessed the leaf's regulatory response to environmental conditions through stomatal conductance (g_{sw}) and leaf-to-air vapor pressure deficit (VPD_{leaf}). The internal efficiency of the photosynthetic apparatus was quantified by measuring the effective quantum yield of photosystem II (Φ_{PSII}) and the electron transport rate (ETR). The overall physiological strain and adaptive responses were monitored via steady-state fluorescence (F_s) and leaf temperature (T_{leaf}).

Osmolality Measurement

To evaluate the osmotic adjustment capacity and the accumulation of osmoprotectants in response to altering water potentials, leaf osmolality was rigorously quantified. The analytical procedure followed the established methodology described by Puniran-Hartley et al. (2014). Representative samples of fully expanded leaves were harvested from each treatment and immediately prepared for preservation. To facilitate cell membrane rupture and the subsequent release of sap for analysis, the collected leaf tissues were stored at -20°C for a duration of 24 hours. Following the freeze-thaw cycle, the samples were processed,

and the osmolality was precisely determined using a Vapor Pressure Osmometer.

Statistical Analysis

Data were represented as the means $\pm$ standard deviation (sd). Differences between treatments were separated by the Duncan's multiple range test (DMRT) at a 0.05 probability level. Statistical analyses were performed by analysis of variance (ANOVA) using R software (R Core Team, R Foundation for Statistical Computing, Vienna, Austria).

Results and Discussion

Vapor pressure deficit (VPD_{leaf}) is increasingly recognized as a key driver of plant physiological processes, primarily through the modulation of leaf stomatal conductance (g_{sw}) and subsequent photosynthetic rates. These responses are dictated by diurnal stomatal dynamics, which are sensitive to variations in irradiance, temperature, and humidity (Li et al., 2018; Eze et al., 2024; Gupta et al., 2025). The results of this study demonstrate that VPD_{leaf} across all investigated rice cultivars (RD61, RD97, RD111, and PTT1) responded to different water management regimes. Specifically, when water management influenced the internal water status of the rice plants, both VPD_{leaf} and g_{sw} exhibited statistically significant changes (Figure 1). The VPD_{leaf} values ranged from 2.27 to 2.85 kPa in the first season and from 2.45 to 4.05 kPa in the second season. These were accompanied by g_{sw} readings that ranged from 0.132 to 0.412 mol m⁻² s⁻¹

¹ and 0.048 to 0.309 mol m⁻² s⁻¹, respectively (Figure 1). The experimental results revealed a pronounced sensitivity of leaf gas exchange to both irrigation regimes and atmospheric demand. Specifically, a significant reduction in g_{sw} was observed as water availability decreased from continuously flooding (CF) to intensive AWD (iAWD) and drought (D) treatments. This downward trend in g_{sw} was strongly coupled with a reciprocal increase in VPD_{leaf} , particularly during the dry season, where environmental conditions were inherently more arid. These observations are in accordance with those of Warren (2008) and Bourbia and Brodribb (2024), who stated that the stomatal aperture usually decreases in response to elevated VPD_{leaf} to preserve plant water status and observed a reverse correlation between VPD_{leaf} and g_{sw} . The transition from conventional AWD (cAWD) to iAWD marked a critical physiological threshold. In the cAWD treatment, g_{sw} remained relatively stable, suggesting that the soil moisture levels at -15 cm were sufficient to meet the plants' transpirational requirements without triggering significant stomatal closure. However, under the more stringent iAWD (-30 cm) regime, the reduction in g_{sw} became statistically significant across most cultivars. This implies that the plant actively limits stomatal aperture to avoid xylem cavitation and preserve leaf water potential when the soil dries to deeper levels. Additionally, the data demonstrates that the drought treatment caused the most physiological stress, with g_{sw} decreasing to the lowest levels ever observed. The high VPD_{leaf} values in this condition indicate that the rice plants were choosing survival

higher than carbon assimilation and were functioning at the boundary of their stomatal regulation.

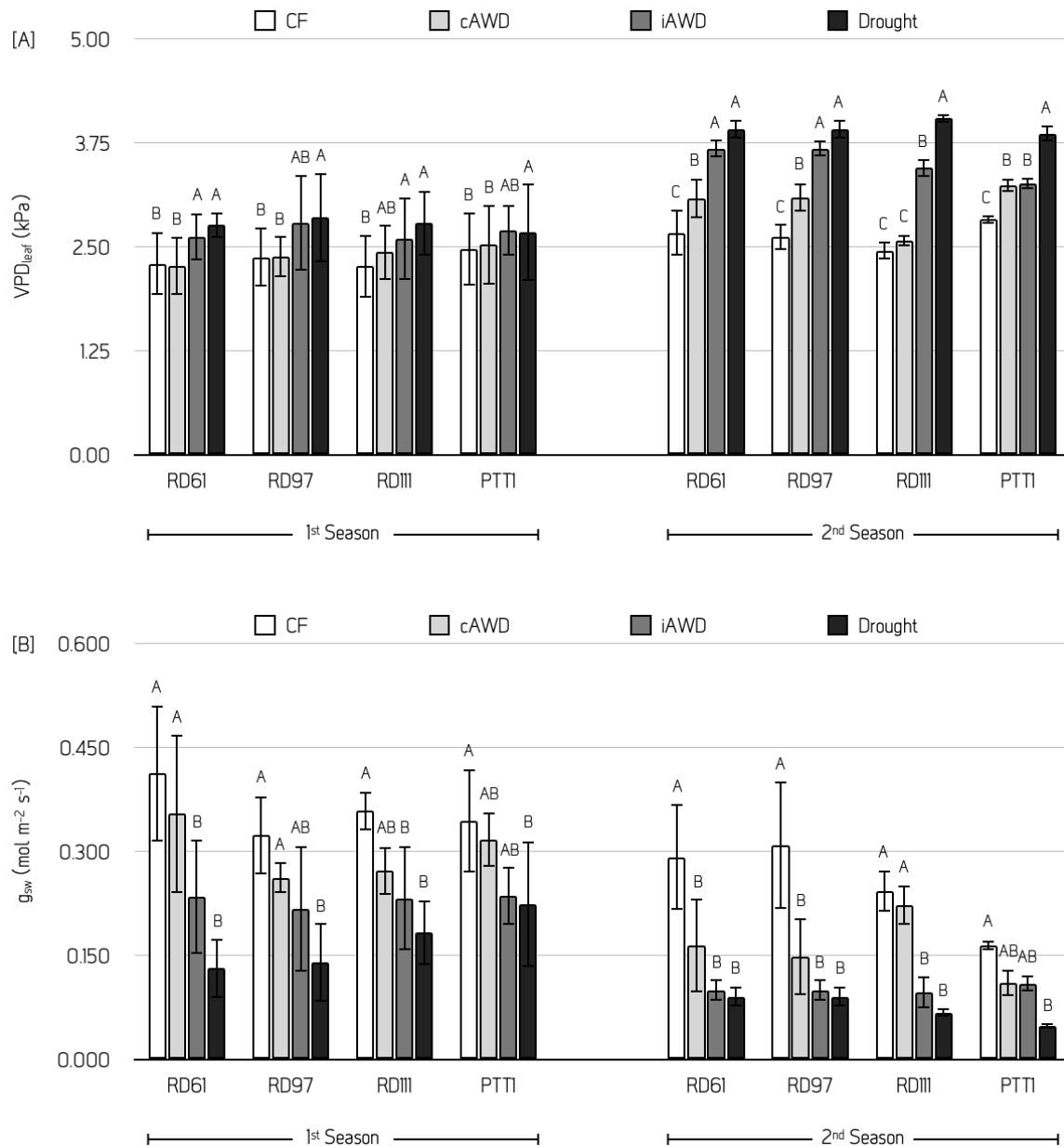


Figure 1 Comparison of [A] leaf-to-air vapor pressure deficit (VPD_{leaf}) and [B] stomatal conductance (g_{sw}) of four rice cultivars (RD61, RD97, RD111, and PTT1) under varying water management regimes: CF (continuous flooding), cAWD (conventional alternate wetting and drying), iAWD (intensive alternate wetting and drying), and D (drought). Data represent the mean values, with error bars indicating the standard deviation (sd). ANOVA was performed, followed by mean comparison with DMRT at p<0.05.

The internal efficiency of the photosynthetic apparatus was significantly influenced by both irrigation regimes and seasonal environmental variations (Figure 2). There were clear differences between the two periods in the effective quantum yield of photosystem II (Φ_{PSII}), which represents the percentage of absorbed light energy employed for photochemistry. Quantum yield ranged from 0.467 to 0.638 in the wet season, while it significantly decreased to 0.228–0.477 in the dry season. A larger level of non-photochemical quenching or possibly stress-induced downregulation of the photosynthetic machinery made exacerbated by the more arid conditions. The electron transport rate (ETR) exhibited a similar seasonal trend to the Φ_{PSII} data. ETR values were kept between 160 and 320 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the first season, and between 146 and 276 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in the second. When compared to the CF, the stability of both Φ_{PSII} and ETR under cAWD indicates that the primary light reactions of the assessed rice cultivars are not intrinsically compromised by modest water-saving measures. However, a metabolic bottleneck is indicated by the notable decrease of electron flux under increasingly severe moisture constraints, particularly in iAWD and drought treatments. As g_{sw} decreases to conserve water, the resulting decline in internal CO_2 availability can lead to an over-reduction of the electron transport chain. Plant must downregulate ETR to reduce the potential of reactive oxygen species (ROS) generation when the

captured solar energy cannot be used efficiently for carbon fixation (Ivanov and Khorobrykh, 2003; Krieger-Liszkay and Shimakawa 2022; Foyer and Hanke, 2022; Gupta et al., 2025). The interplay between light intensity and temperature stress provides an additional explanation for the observed seasonal variation in photochemical performance. When the water status was preserved, the continuously higher solar radiation throughout the first season might have sustained a more robust electron flux despite higher peak temperatures. On the other hand, a synergistic stress impact was probably caused by the environmental profile of the second season, which was marked by much lower minimum temperatures and greater VPD_{leaf} . An imbalance between the photochemical reaction and CO_2 fixation frequently results from the combination of cold-induced metabolic degradation and water scarcity in the iAWD and drought treatments (Arena and Vitale, 2018; Li et al., 2024).

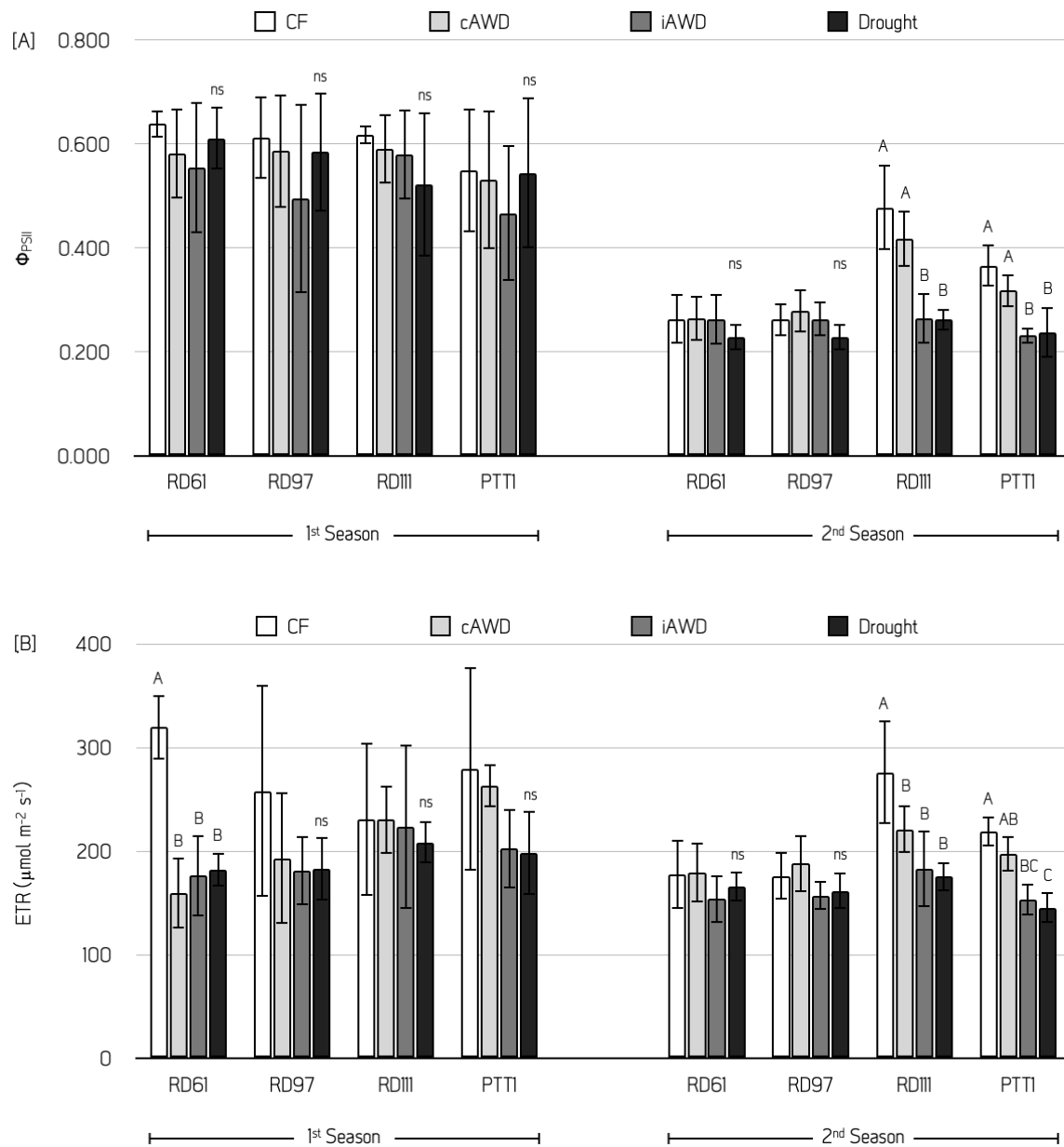


Figure 2 Comparison of [A] effective quantum yield of photosystem II (Φ_{PSII}) and [B] electron transport rate (ETR) of four rice cultivars (RD61, RD97, RD111, and PTT1) under varying water management regimes: CF (continuous flooding), cAWD (conventional alternate wetting and drying), iAWD (intensive alternate wetting and drying), and D (drought). Data represent the mean values, with error bars indicating the standard deviation (sd). ANOVA was performed, followed by mean comparison with DMRT at $p < 0.05$; “ns” indicates no significant difference.

The interaction between heat regulation and light energy dissipation provides important evidence of the physiological stress that rice cultivars encounter under varying water regimes. Throughout the two cultivation periods, chlorophyll fluorescence (F_s) and leaf temperature (T_{leaf}) were crucial indicators of the plants' adaptive responses to atmospheric demand and water scarcity. As shown in Figure 3, F_s values exhibited a marked seasonal disparity. During the wet season, F_s remained relatively stable within a narrow range of 115 to 168. However, in the dry season, there was a significant upward shift, with values climbing to 154–274. This elevation in F_s , particularly under the iAWD and drought treatments, suggests a reduction in the efficiency of photochemical quenching. As g_{sw} declined, the resulting limitation on CO_2 fixation likely led to an accumulation of unused excitation energy within the pigment system, manifested as higher basal fluorescence. The leaf temperature data further elucidated the metabolic consequences of water-saving irrigation. In the wet season, T_{leaf} remained within a relatively

tight corridor of 30.9–33.0 °C. This stability indicates that even under moderate AWD, the plants maintained sufficient transpirational cooling to avoid thermal stress. Conversely, in the dry season, T_{leaf} exhibited a broader and more stressful range of 28.4–33.9°C. The highest leaf temperatures were consistently recorded in the iAWD plots and drought, where restricted stomatal aperture limited the dissipation of latent heat. The concurrent increase in both F_s and T_{leaf} under severe water deficit conditions indicates a breakdown in the plant's energy dissipation and photosynthetic regulation mechanisms. These physiological responses collectively demonstrate the detrimental effects of drought stress on plant energy balance and photosynthetic stability. (Genty et al., 1987; Kusvuran, 2012; Chowdhury et al., 2017; Zhuang et al., 2020). The demand for transpirational cooling increased in the dry season due to the synergistic effect of reduced relative humidity and high VPD_{leaf} . Therefore, rice was forced into a condition of thermal imbalance by the iAWD and drought treatments' lack of available soil moisture.

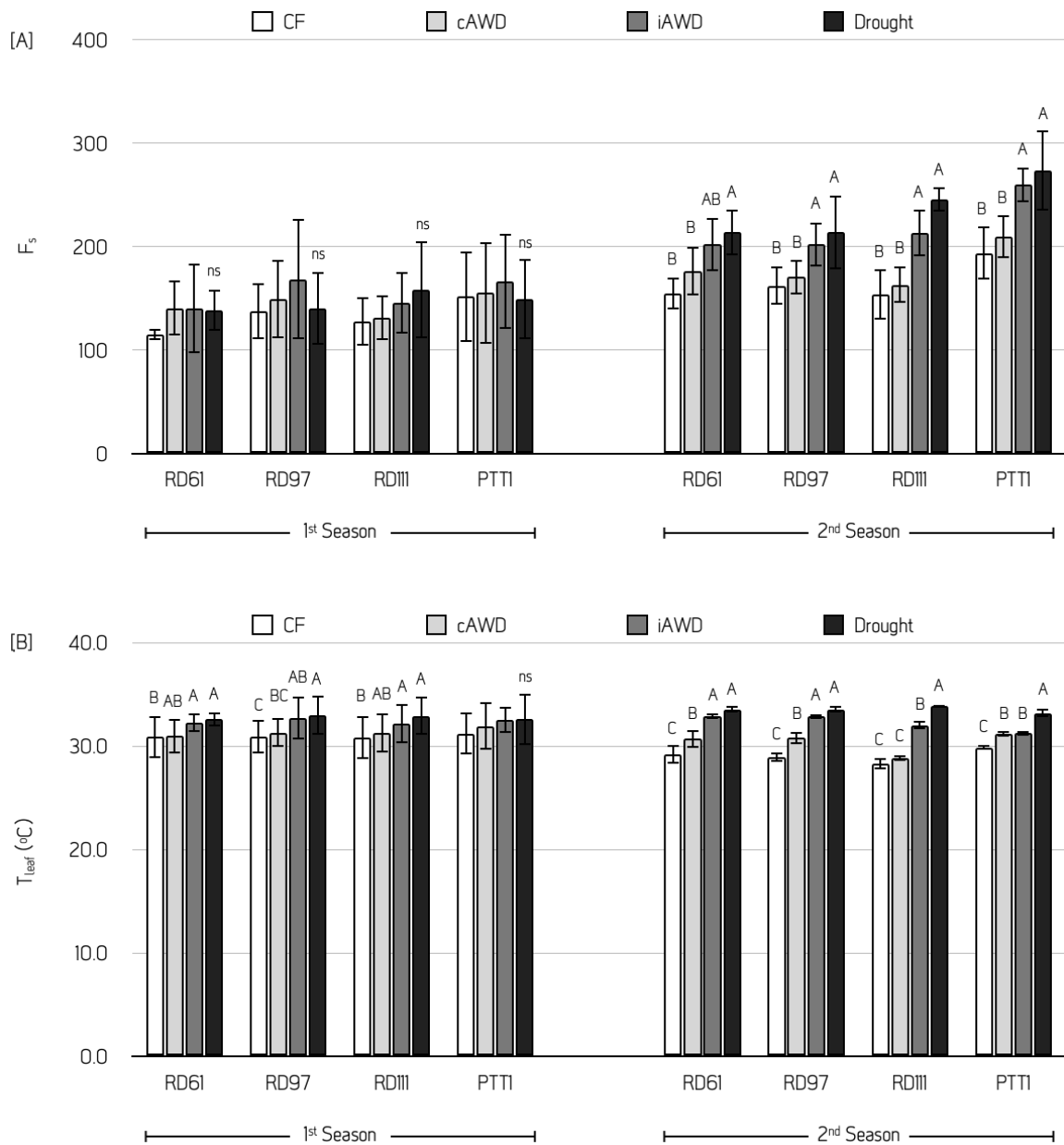


Figure 3 Comparison of [A] chlorophyll fluorescence (F_s) and [B] leaf temperature (T_{leaf}) of four rice cultivars (RD61, RD97, RD111, and PTT1) under varying water management regimes: CF (continuous flooding), cAWD (conventional alternate wetting and drying), iAWD (intensive alternate wetting and drying), and D (drought). Data represent the mean values, with error bars indicating the standard deviation (sd). ANOVA was performed, followed by mean comparison with DMRT at $p < 0.05$; “ns” indicates no significant difference.

Grain yield was the final result of seasonal environmental variable and irrigation management (Figure 4). CF and conventional cAWD treatments consistently produced the highest yields across all cultivars, whereas iAWD and drought conditions resulted in yield reductions that were significantly noticeable. The results confirm that cAWD is a highly effective strategy for maintaining yield levels comparable to traditional flooding while reducing water inputs. However, the shift to iAWD consistently triggered significant yield losses, particularly when combined with the unfavorable atmospheric conditions of the dry season. These findings highlight that the adoption of intensive water-saving regimes must be carefully calibrated against cultivar-specific sensitivity and seasonal weather forecasts to ensure regional food security within the Water-Energy-Food (WEF) Nexus. Specifically, the physiological data from this study clarifies how exceeding the safe threshold under iAWD and drought treatments directly disrupts the 'Food' component of the nexus. The severe suppression of Φ_{PSII} down to 0.228–0.477 and ETR down to 146–276 $\mu\text{mol m}^{-2} \text{s}^{-1}$), driven by

high VPD_{leaf} and low humidity in the dry season, underscores a critical metabolic disruption. When g_{sw} is restricted to conserve 'Water', the loss of evaporative cooling leads to elevated T_{leaf} , showing that aggressive water-saving mechanisms can backfire by inducing lethal thermal and metabolic strain on the crop. In contrast, the robust performance of cAWD—which stabilized grain yields at a high potential of 1.1 ton in the wet season while protecting photosynthetic integrity demonstrates a successful synergy within the WEF Nexus. By maintaining soil moisture within the safe -15 cm threshold, cAWD optimizes 'Water' productivity without sacrificing 'Food' security. Furthermore, this calibrated approach mitigates the 'Energy' footprint typically required for excessive pumping in continuous flooding systems, while preventing the crop failure risks associated with uncalibrated iAWD. Therefore, optimizing water regimes based on real-time physiological thresholds is not merely an agronomic choice, but a core requirement for balancing resource trade-offs within the WEF Nexus under shifting seasonal climates."

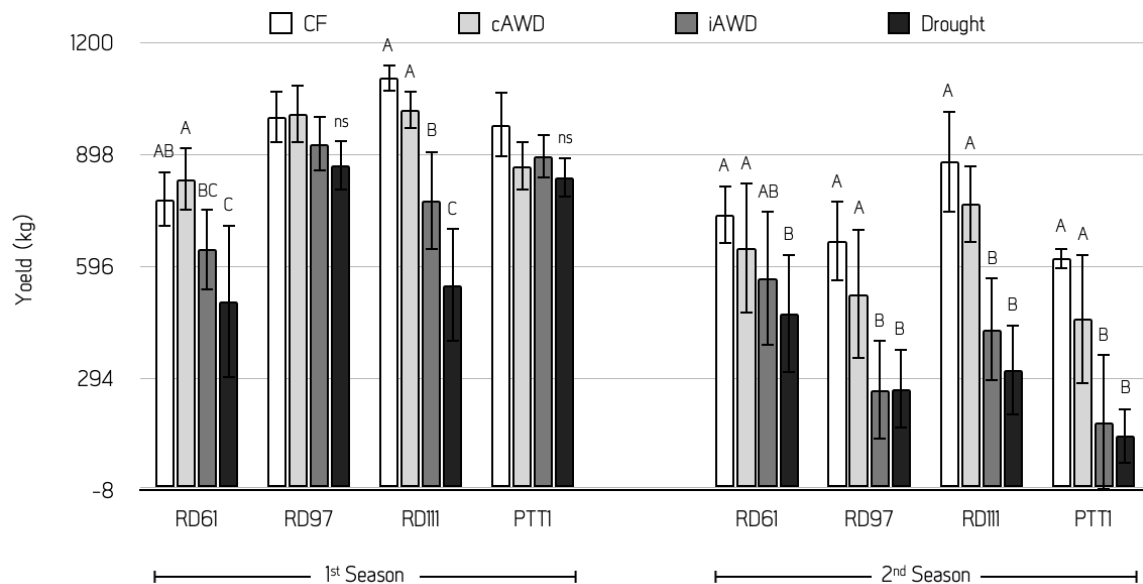


Figure 4 Comparison of grain yield of four rice cultivars (RD61, RD97, RD111, and PTT1) under varying water management regimes: CF (continuous flooding), cAWD (conventional alternate wetting and drying), iAWD (intensive alternate wetting and drying), and D (drought). Data represent the mean values, with error bars indicating the standard deviation (sd). ANOVA was performed, followed by mean comparison with DMRT at $p < 0.05$; “ns” indicates no significant difference.

Beyond agronomic performance, the implementation of optimized water regimes plays a pivotal role in reducing the carbon footprint of rice cultivation. In this study, cAWD provided a strategic approach for mitigating greenhouse gas emissions while successfully maintaining conventional physiological functioning and yield potential. The periodic transition from flooded to aerobic soil conditions under cAWD inhibits methane-producing microbial activity while preventing the severe water deficit stress seen in iAWD and drought treatments. In addition to the severe photosynthetic inhibition (Φ_{PSII} dropping to 0.228) and stomatal limitations reported here, prolonged soil drying (as observed in iAWD) can significantly suppress CH_4 emissions, but it frequently causes an increase in N_2O emissions

due to enhanced nitrification-denitrification processes (Wichaidist et al., 2003; Wichaidist et al., 2025b). Consequently, this evaluation's stated cAWD approach offers a fair "win-win" scenario. By effectively reducing global warming potential (GWP) through controlled methane suppression, it avoids the serious metabolic risks connected with going over the -15 cm threshold and provides a sustainable paradigm for different four Thai rice cultivars.

Conclusion

The findings of this research provide critical insights into the physiological and agronomic trade-offs associated with water-saving irrigation in

tropical rice cultivation. The study demonstrates that cAWD is a robust water management strategy that maintains photosynthetic capacity and grain yield levels equivalent to traditional continuous flooding. In contrast, iAWD and drought induce severe physiological stress characterized by significant reductions in soil water content leading to significant yield losses, especially in cultivar RD111. In the context of the Water-Energy-Food (WEF) Nexus, these findings suggest that increasing water-saving practices (iAWD) is an effective approach for enhancing water productivity, but its effectiveness is highly dependent on specific conditions. The implementation of more rigorous AWD practices cannot be applied generalized; instead, it requires specific data between the stress tolerance thresholds of each cultivar and seasonal environmental conditions. Therefore, future scaling of advanced water-saving technologies must shift from broad recommendations toward prescriptive management, using real-time meteorological monitoring paired with elite, climate-resilient cultivars.

Recommendations

Optimizing water-use efficiency is critical to address the combined challenges posed by climate change and the high water demands of traditional rice farming. Considering rice's vulnerability to water shortages, adaptive irrigation methods must be carefully fine-tuned. This research illustrates that cAWD serves as a reliable baseline practice,

effectively balancing resource conservation with the physiological needs for maintaining yield. However, the implementation of more intensive water-saving strategies, such as iAWD, should not be universally applied; instead, their use should be strictly based on the specific physiological limits of various cultivars and real-time weather monitoring to prevent significant metabolic stress and yield reductions. In the end, reducing climate-related risks and assuring regional food security relies on the precise alignment of specific hydrological limits with drought-resistant cultivars.

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