Paddy and Water Environment
https://doi.org/10.1007/s10333-024-01012-5

ARTICLE

Assessing the feasibility of alternate wetting and drying (AWD) technique for improving water use efficiency in dry-season rice production

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Received: 30 November 2023 / Revised: 26 August 2024 / Accepted: 18 November 2024

Abstract
Alternate Wetting and Drying (AWD) Technique has effectively conserved water in various regions, particularly Asia. However, there is a lack of research on the feasibility of AWD in different paddy soil ecosystems, particularly in Cambodia. We evaluate the possibility of saving water in dry rice production in Cambodia by quantifying the effects of AWD on rice yield and water use efficiency (WUE) with varying varieties and soil properties. We tested AWD at two different threshold levels: safe AWD (AWD15), when the perched water table drops to 15 cm below the soil surface, and mild AWD (AWD20), when it drops to 20 cm below the soil surface. Five field experiments were conducted from 2021 to 2023. Associative causal relationships between measurable and latent variables of rice grown under CF and AWD were tested using partial least squares structural equation modeling (PLS-SEM) and an analysis of variance (ANOVA).Our results showed that safe and mild AWD did not significantly affect grain yield, yield components, harvest index (HI), and root growth compared to conventional flooding (CF). Despite similar yields, AWD significantly reduced total water inputs by 10–30% in AWD15 and 22–24% in AWD20 compared to CF. Among the AWD treatments, AWD15 exhibited the highest WUE. Our study found that on sandy loam soil, both AWD15 and AWD20 treatments improved WUE over CF, and clay soil's WUE was higher than sandy soil. However, clay soil's WUE in AWD did not improve over CF. Our findings demonstrate that implementing safe and mild AWD has significant potential for rice growing on sandy loam.

Keywords Alternate wetting and drying · Variety · Soil property · Water use efficiency · Water savings · Dry season rice

Introduction

By 2050, there will be 30 million people living in Cambodia, doubling the country's present 16 million inhabitants (MAFF 2019). The agricultural sector, of which rice is the main product, accounts for 24.4% of Cambodia's GDP (MAFF 2022). However, dry season rice covers only 19% of the paddy land and produced 26.15% of the total paddy yield (wet and dry paddy) of 11,700 million tons between 2023 and 2024 (Sokkea 2024). This is because of the limits in hydraulic infrastructure making farmers who reside distant from water sources unable to crop during the dry season. Thus, rice is predominantly grown in the wet season around the floodplains, where the Mekong River or Tonle Sap Lake's yearly floods provide irrigation water. Apart from the restricted availability of water supplies in the dry season, farmers face significant uncertainty due to drought. More days of dryness, heavier rainfall events, and higher minimum and maximum temperatures were predicted for Cambodia (NCSD 2015). More severe floods and droughts were also predicted to harm 10% of Cambodia's GDP by 2050 (World Bank 2021). To improve the economy and cope with the expected population growth, Cambodia must increase food production. One of the key strategies to boost the overall output of crops is to improve the cultivation of dry season rice.

The conventional rice growing method is highly productive but requires flooding the rice between 5 and 10 cm throughout the growth season (MAFF 2019). Thus, much

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Published online: 01 December 2024

water is needed, and water productivity could be more efficient. There are plenty of water-saving methods that have been developed to improve water use efficiency (WUE), including raise bed systems for direct rice seeding (Choudhury et al. 2007), direct seeding (Weerakoon et al. 2011), the system of rice intensification (Hardy et al. 2016), non-flooded mulching cultivation (Xu et al. 2007), aerobic cultivation (Lampayan et al. 2010), and alternate wetting and drying (AWD) irrigation (Carrijo et al. 2017).

Because of its simplicity of use, AWD is among the most employed water-saving techniques. It has been used worldwide, including in Asia (Arai et al. 2021; Sriphirom et al. 2019), Europe (Oliver et al. 2019; Monaco et al. 2021), the United States (Atwill et al. 2023; Runkle et al. 2018), and Africa (de Vries et al. 2010). Carrijo et al. (2017) conducted a meta-analysis of 56 distinct investigations and found that 31% of the studies were from China, and more than 80% were from Asia. Fields under AWD are exposed to intermittent drying cycles during the growth season. As soon as the drying criteria are reached, fields are re-ponded. (Isafaq et al. 2020). Ishfaq categorized the six categories in which AWD thresholds are set, as follows: 1) soil water potential, 2) a certain number of days without flooding; 3) the emergence of surface cracks in the soil, 4) the plant exhibiting signs of water stress, 5) the dropping of the field water level (FWL) to a specific soil depth, and 6) the use of ditch irrigation. For the rural farmers of Mekong, using PVC tubes for water level monitoring was a more straightforward and convenient approach. Isafaq et al. (2020) defined AWD as (1) safe when the soil water potential (SWP) was > -10 kPa and the FWL was ≤ 15 cm (AWD15); (2) mild/moderate when the SWP was ≥ -20 kPa and the FWL was = 15–20 cm (AWD20); and (3) severe when the SWP was < -20 kPa and the FWL was > 20 cm. AWD has numerous advantages over the conventional continuous flooding (CF) method. For instance, it has the potential to save water in sub-tropical monsoon regions and tropical semi-arid regions by 20–40% (de Vries et al. 2010; Yao et al. 2012). Additionally, according to de Vries et al. (2010) and Lampayan et al. (2015), AWD could sustain low weed pressure and increase nitrogen recovery efficiency. AWD had improved soil redox potential and aeration; whereas, CH_4 levels were approximately 34% lower than in CF (Feng et al. 2021).

Additionally, there have been reports of varying effects on yield under the AWD system compared to the CF system, with some studies indicating an increase (Liang et al. 2016; Jabran et al. 2016), others showing similar results (Yao et al. 2012), and some suggesting a decrease (Feng et al. 2021; Lagomarsino et al. 2016). These conflicting findings point to the necessity of designing and implementing site-specific irrigation management strategies that consider the soil's characteristics, drainage frequency, the length of flooding cycles, and the variety's adaptation (Mazza et al. 2016). On the other hand, little research has been done to examine AWD in depth for different varieties and paddy soil environments.

Also, apart from Sandhu et al. (2017) research, there is a lack of scientific data supporting adopting safe AWD practices in Cambodia. Sandhu concentrated on suitable root characteristics to increase yield under safe AWD. Compared with conventional flooding (CF), Sandhu's experiment in Cambodia showed that AWD15 improved yields by 7 to 9% and saved 3 to 7% of the water. These improvements were relatively small in encouraging farmers to adopt AWD. Therefore, Sandhu recommends the identification of new rice genotypes that can consistently produce high or stable yields under AWD across different ecosystems, while achieving an average water saving of 20% in rice cultivation. In addition to safe AWD, it would be worth investigating the possibility of using mild AWD in Cambodia to save more water and prevent yield penalties.

The specific objectives of this study were to (1) test the possibility of saving water in dry rice production in Cambodia by quantifying the effects of AWD on rice yield and irrigation water productivity using varying varieties and soil properties. In addition, the interactions between water-saving irrigation regimes, variety, and soil properties were studied. (2) We also investigate the potential for further reducing water input and increasing WUE by increasing the AWD threshold from -15 cm to -20 cm below the soil. To test the possibilities for saving irrigation water, we chose four sites that differed in soil property and fertility background and conducted the experiments in dry seasons from 2021 to 2023.

Materials and methods

Experimental sites

In total, five experiments were conducted in the dry season, as shown in Table 1. Three experiments were conducted at the Cambodian Agricultural Research and Development Institute (CARDI) in Phnom Penh (11°28' N, 104°48' E) from 2021 to 2023. Two locations were used for CARDI experiments: site A was used in 2021–2022, and site B was used in 2023. The other two experiments were conducted in Kampong Thom Province (KTM) simultaneously during the dry season 2022. K1 (12°33' N, 105°2.6' E) is 300 m from K2 (12°33' N, 105°2.8' E).

CARDI's soil types were classified as red-yellow podzols (Crocker 1962). Crocker (1962) classified soil at K1 as lacustrine alluvial and K2 as alluvial lithosol. Prateah Lang is a soil found on the colluvial–alluvial plains and old alluvial terraces. It is composed of a subsurface with a clayey or loamy texture and a sandy topsoil that is less than 40 cm

Table 1 Variety, amount of fertilizer, and date of the experiment at CARDI in 2021–2023 and in Kampong Thom Province in 2022 under continuous flooding (CF) and alternate wetting and drying (AWD) irrigation

Location	Regime	Variety	Fertilizer amount	Date of experiment
CARDI: Site A	CF, AWD15	OM5451, CAR15, Sen Kra Ob, Sen Pidor	60:30:30 $N:P_2O_5:K_2O$	Feb–May, 2021 Mar–June, 2022
Site B				Jan–May, 2023
KTM: K1 and K2	CF, AWD15, AWD20	CAR15	60:30:30 $N:P_2O_5:K_2O$	Jan–Apr, 2022

thick (White et al. 1997). This soil occupies 25 -30% of the rice land and is the dominant type in Cambodia. CARDI and K1, which contain Prateah Lang soil type, were chosen to match actual practice. However. for comparison, the K2 soil type (commonly known as the Bakan soil type) was also chosen.

Cambodia is characterized by a tropical climate influenced by monsoon winds, causing 6 months dry and 6 months wet. The dry season occurs from November to April, and the rainy season occurs between May to October. Annual precipitation levels vary from 1400 to 4000 mm (FAO 2024) across the country. In Cambodia, the average daily maximum temperature (Tmax) is approximately 28 °C, and the average daily minimum temperature (Tmin) is around 22 °C. The mean Tmin consistently stays above 25℃ throughout the monsoon season, although the mean Tmax can go over 35℃ during the pre-monsoon months (April and May). On the other hand, typical rainfall in the dry season typically occurs with unpredictable patterns and amounts.

The daily weather data for CARDI, which included air temperatures, rainfall, wind speed, relative humidity, and solar radiation, came from an automated weather station (iMETOS 3.3, Pessl Instruments, Werksweg, Weiz, Austria) situated at the experimental field; while, KTM's data came from the Ministry of Water Resources and Meteorology. The weather station of the ministry is located less than 1 km away (12°33' N, 105°2' E). ETo was estimated using the Penman–Monteith Method.

Soil sampling

Prior to transplanting, soil samples were collected from various horizons within a 0.8 m depth column at each site. For every horizon, three replicates were collected. The soil texture was measured using hydrometers (ASTM D 422, Eijkelkam, Nijverheidsstraat, EM Giesbeek, Netherlands). Field capacity (FC) and permanent wilting point (PWP) were measured using a pressure plate (1600F1 and 1500 F2, Eijkelkam, Nijverheidsstraat, EM Giesbeek, Netherlands) at the pressure of -33, and -1500 kPa, respectively. Soil saturation (SAT) was derived from the bulk density determined by the ring method. Saturated conductivity (Ksat) was estimated using KSAT instrument (Meter Group, Pullman, WA, USA).

Experiment set up

At CARDI, the experimental site (20×45 m^2) was split into two blocks, with alternate wetting and drying (AWD) and continuously flooded (CF) replicates adjacent to each other. Within each block, there were individual randomized plots of four rice cultivars and three replications. The size of each plot was 5×5 m^2. The rice varieties included Sen Kra Ob (*SK*), CAR15 (*CAR*), Sen Pidor (*SP*), and check rice: *OM5451* (OM). The varieties were short-cycle taking between 89 – 100 days after transplanting (DAT) to maturity. A 60:30:30 $N:P_2O_5:K_2O$ fertilizer ratio was used. The experiment designs for the two fields (K1 and K2) in Kampong Thom were identical. A split–split plot with four replications of the experimental design was applied under three main irrigation management methods: CF, AWD15, and AWD20. In Kampong Thom, only one variety, which was CAR15, was tested. The sub-subplot sizes were 5×5 m^2. Figure 1 represents a diagram showing the area and shape of the experimental plots in CARDI and Kampong Thom province.

To prevent lateral seepage, plastic film was placed over the bundles. To stop water from flowing from CF to AWD treatments, the main plots were divided by gaps ranging from three to five meters. During the 7 days following transplanting until the 10 days before maturity, the ponded water depth in the entire field was maintained within the CF regime between 1 and 5 cm. PVC tubes measuring 35 cm in length and 10 cm in diameter were inserted into the AWD treatment at a depth of -15 cm for AWD15 and -20 cm for AWD20, respectively. The tube had holes drilled in it on all sides.

In the AWD treatment, the land was reflooded to 5 cm after the field water disappeared in the PVC tubes. Three weeks following transplantation, the first AWD treatment was started. This cycle was repeated up to the reproductive stage when the field was maintained submerged from one week before flowering until 10 days before harvesting. During the AWD cycle, surplus water from unexpected rainfall was drained.

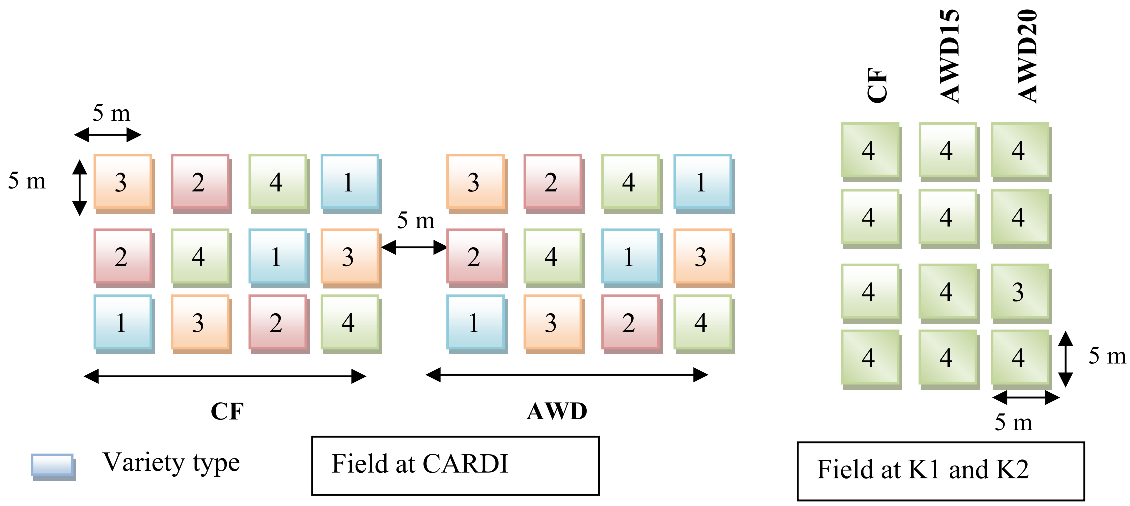

Fig. 1 Areas and shapes of the experimental plots at CARDI and Kampong Thom province (K1 and K2)

Table 2 Timing, frequency, and amount of fertilization applied in the experiments

Component	60N:30P_2O_5:30K_2O	Before trans-planting	14th DAT	30th DAT
N	46–00-00	0.5 kg	1.2 kg	1.2 kg
P_2O_5	18–46-00	0.8 kg		
K_2O	00–00-60	1.1 kg		

The same amount of fertilizer, 60:30:30 N:P_2O_5:K_2O was applied to all field experiments. Table 2 specifies the timing, frequency, and amount of fertilization. Irrigation was supplied by tubes connected to the pump. Due to technical impossibility, without the water meters, the irrigation volume was determined by multiplying the cross section area of a plot by the water height at a plot's reference point, without accounting for the infiltration rate. To confirm that the infiltration rate was negligible, the time series soil moisture content of Site B was examined. In 2023, hourly volumetric soil moisture content (SMC) was measured by Teros 12 (Meter Group, Pullman, WA, USA) from the 35th day after transplanting (DAT) until the 65th DAT (during AWD15 cycle) at 0.10 m depths in all AWD plots. An assumption was made that the results of the infiltration test from Site B represented all experimental sites because the soil texture of this site is similar to that of Site A and K1.

Water saving was calculated against control treatment. Water use efficiency (WUE) was defined as the grain yield per unit of total water input, including irrigation and precipitation.

Plant materials and phenological record

Twenty-one-day-old seedlings were transplanted at a hill spacing of 20 cm by 20 cm in each trial. The flowering date was determined as the point at which 50% of the rice in a plot began to produce flowers. The maturity date was then calculated as 30 days after the flowering date.

Measurement of yield, yield components, and root depth

At maturity, 10 hills were taken randomly outside a 6 m^2 area, where grain yield was determined, avoiding the first and second row and column of rice in the plot to eliminate the border effect. Plant height was measured from the plant base to the tip of the highest leaf. Panicle number was recorded from those 10 hills. Three subsamples of panicles were randomly chosen from the ten plants. Within the 3 subsamples, the filled and unfilled spikelets were identified by squeezing. The total number of panicles per meter square equals the total panicle per hill multiplied by the number of hills per m^2, which is 25. Aboveground total biomass was the total dry matter of straw, rachis, and spikelets after oven-drying to constant weight at 70 °C for 48 h. Spikelets per panicle, grain-filling percentage (100 × filled spikelets/total spikelets), and harvest index (HI) (100 × filled spikelet weight/aboveground total biomass) were calculated. Grain yield was determined from a 6 m^2 area in each plot and adjusted to the standard moisture content of 0.14 g H_2O/g fresh weight. One plant per plot was recorded for an effective root depth, defined as a depth where 70% of roots are located.

Time series measurement

Additionally, time series measurements of the total aboveground biomass and canopy cover were recorded. The aboveground biomass of 10 plants was collected bi-weekly and oven-dried at 70 °C for 48 h. Weekly data on canopy cover was collected by digital photos shot at a constant height of 1.8 m, three points per replicate. By dividing the total number of crop pixels by the total number of picture pixels, the fraction of the canopy covering the soil was determined. Three by four plants in the center of the image were retained to eliminate the border effect, which produces torsion in an image and results in a greater value of canopy cover. The analysis of the images was done using Adobe Photoshop 2020.

Statistical analysis

For rice grown under CF and AWD, associative causal relationships between measurable and latent variables were tested using partial least squares structural equation modeling (PLS-SEM). A collection of manifest variables can be used to express the latent variables. Known also as observed variables, manifest variables are amounts that are directly measurable or observable. Although latent variables are not directly observable, they can be created using one or more manifest variables and a theory or hypothesis. Measurement models and structural models are typically included in PLS-SEM. PLS-SEM is more suitable for exploratory research on small samples and can effectively evaluate the interaction between variables (Fan et al. 2016; Tenenhaus et al. 2005).

In this study, 10 evaluation indicators were compiled and calculated using grain yield, WUE, harvest index (HI), effective root depth, biomass, number of filled spikelets, percentage of filled spikelets, total number of spikelets, number of panicles per m^2, and plant height as manifest variables, and grain yield, yield components, WUE, soil, and variety as latent variables in PLS-SEM. Composite dependability (CR) (Jöreskog 1969) was used to assess the internal coherence dependability. A CR of greater than 0.7 and no less than 0.6 is the standard expectation. Convergent validity was verified using the Average Variance Extracted (AVE), which must be greater than 0.5 (Nasution et al. 2020).

R (version 4.2.2) was used to analyze the data, and an analysis of variance (ANOVA) was done at a 95% significance level. The Tukey test was used to perform pairwise comparisons. Smart PLS 4 software was used to analyze and demonstrate PLS-SEM (Ringle et al. 2015).

Results

Weather conditions during the growing seasons

AWD cycles for short-cycle rice (growing span of 90–120 days) began on the 21st DAT and ended a week before the flowering stage, on average, the 53rd DAT. AWD cycles in all experimental sites followed the theoretical scheme. In contrast, at CARDI in 2022, the AWD cycles were interrupted by unexpected rainfall (Fig. 2 and 3). The unexpected rainfall was drained out from the field afterward.

Mean daily ETo were 5 mm and 3 mm at CARDI and KTM, respectively. Except for 2022 at CARDI, where total rainfall is 15% higher than total ETo, total rainfall in the dry season of the other experiments met only 18% and 40% of total ETo (464 mm on average).

Physical characteristics of experimental soils

As Table 3 shows, the soil characteristics at each trial location are entirely unique. Except for K2, which is sandy clay loam, all other sites have a sandy loam texture at the top but a different texture at the bottom, and their ability to retain water varies. Among all sites, K2, which is sandy clay loam, has the lowest Ksat, while K1 has the biggest Ksat.

Phenology

Tables 4 and 5 demonstrate that rice phonology clearly varied by variety and location. In AWD, flowering occurred one to three days before or after CF. For both regimens, the difference in flowering dates ranged from three to ten days. While the flowering date of all varieties in Site B increased by 7 to 9 days compared to Site A, Sen Pidor was 2 to 3 days shorter.

Compared to K2, K1's flowering date was ten days later. AWD15 and AWD20 flowered two days after CF in K1; whereas, AWD20 appeared two to three days before CF and AWD15 in K2. Throughout all trial plots, the flowering date standard deviation varied from 1 to 3 days. However, there was no significant difference between the phenology of rice grown under different water regimes in all experiments.

The average total amount of water input for each trial is shown in Table 6. At CARDI, CF was irrigated an average of 15 times in 2021, 9 times in 2022, and 18 times in 2023. The average total input, including rainfall under CF, was 909, 462, and 998 mm for Site A in 2021, 2022, and Site B in 2023, respectively. Although the topsoil texture of Site B was similar to that of Site A (sandy loam), it did use more water (Fig. 3). Site B used an average of 97% and 20% more water than Site A, in the complete dry season of 2021 and when interfered with rainfall in 2022,

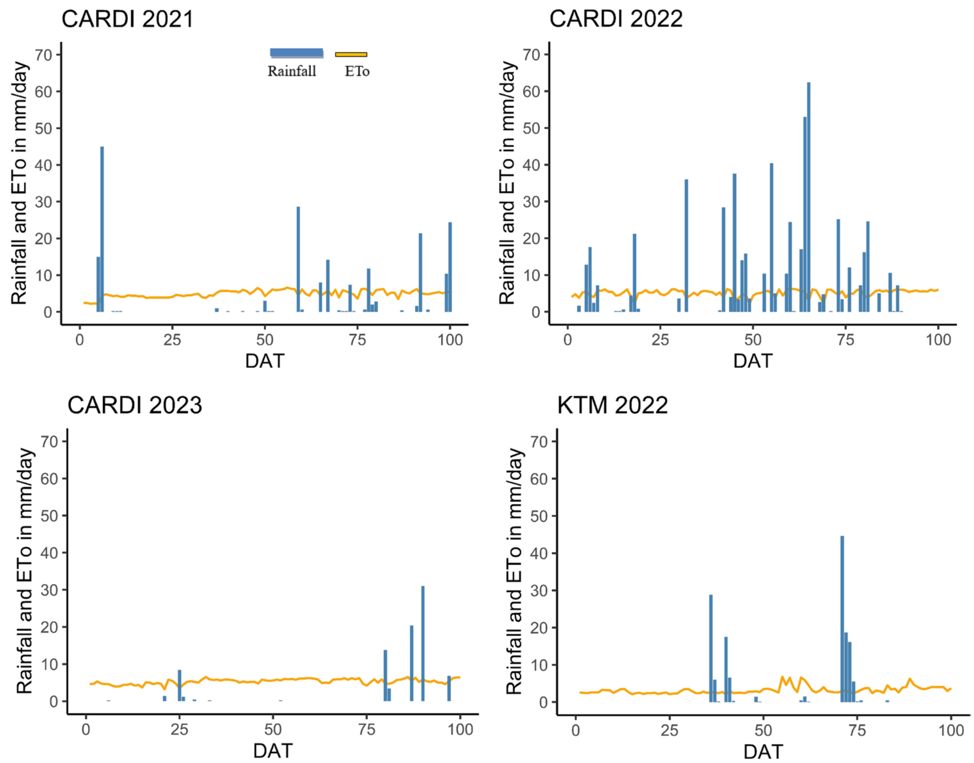

Fig. 2 ETo and rainfall at four experimental fields (Site A and Site B in CARDI, K1 and K2 in Kampong Thom Province), over three growing seasons, 2021, 2022, and 2023

respectively. This could be caused by the large Ksat at the top layer at Site B, which is 160 mm/day, compared to only 16 mm/day at Site A, which is ten times less. Furthermore, Site B's water holding capacity (the difference between FC and SAT) is lower than Site A's.

AWD15 saved, on average, 20% at Site B and between 11 to 31% at Site A as compared to CF. Table 6 shows that in 2022, the rainfall contributed 13% (K1) and 30% (K2) of the total irrigation due to the varying growth length. Under CF, K1 and K2's average total water intake, including rainfall, was 1113 mm for K1 and 500 mm for K2. For CF, there were 22.25 irrigations in K1, compared to 12.25 irrigations in K2. AWD15 and AWD20 saved 18–24% and 20–22%, respectively, compared to CF. Overall, when tested on various soil ecosystems, AWD15 decreased water input by 11% to 31%; while, AWD20 saved 22–24%.

Furthermore, soil texture is a significant factor in determining the quantity of irrigation needed. The average water needs for sandy loam (Site A, Site B, and K1) was 24 to 80% higher than that of sandy clay loam (K2) when there was no interruption by rainfall. Ksat was the driver for the length of the irrigation cycle and irrigation frequency. In this study, the value of Ksat at each location is negatively correlated with the total amount of irrigation. The irrigation cycle in AWD cycles varied depending on soil texture and ranged from 5 to 10 days (Fig. 3). Compared to the other two sites, soil with greater Ksat, such as Site B and K1, loses water through percolation more quickly and requires more irrigation, as indicated in Fig. 3.

Volumetric moisture content before and after irrigation

Figure 4 shows that at a soil depth of 5 to 15 cm, there was no significant difference in soil moisture content (SMC) one hour before and after each irrigation. This indicates that infiltration could be negligible when irrigation takes less than an hour. In our experiments, irrigation lasted 20 to 40 min in each plot. This result supports our hypothesis that the irrigation volume equals the water height times the plot area.

Modeling the impact of manifest and latent factors on yield and WUE using PLS-SEM

The initial PLS-SEM models of the yield and WUE distribution from 2021 to 2023 illustrate the overall relationships between latent and manifest variables. The results indicate that among the 7 manifest variables, only HI, panicle number/m^2, and yield were well explained by the latent variable "Yield", with significant outer loadings of $p < 0.01$ and loading values of = 0.834, 0.657, and 0.929, respectively. The remaining 4 manifest variables are classified as "Yield component" latent variables. It was shown that the

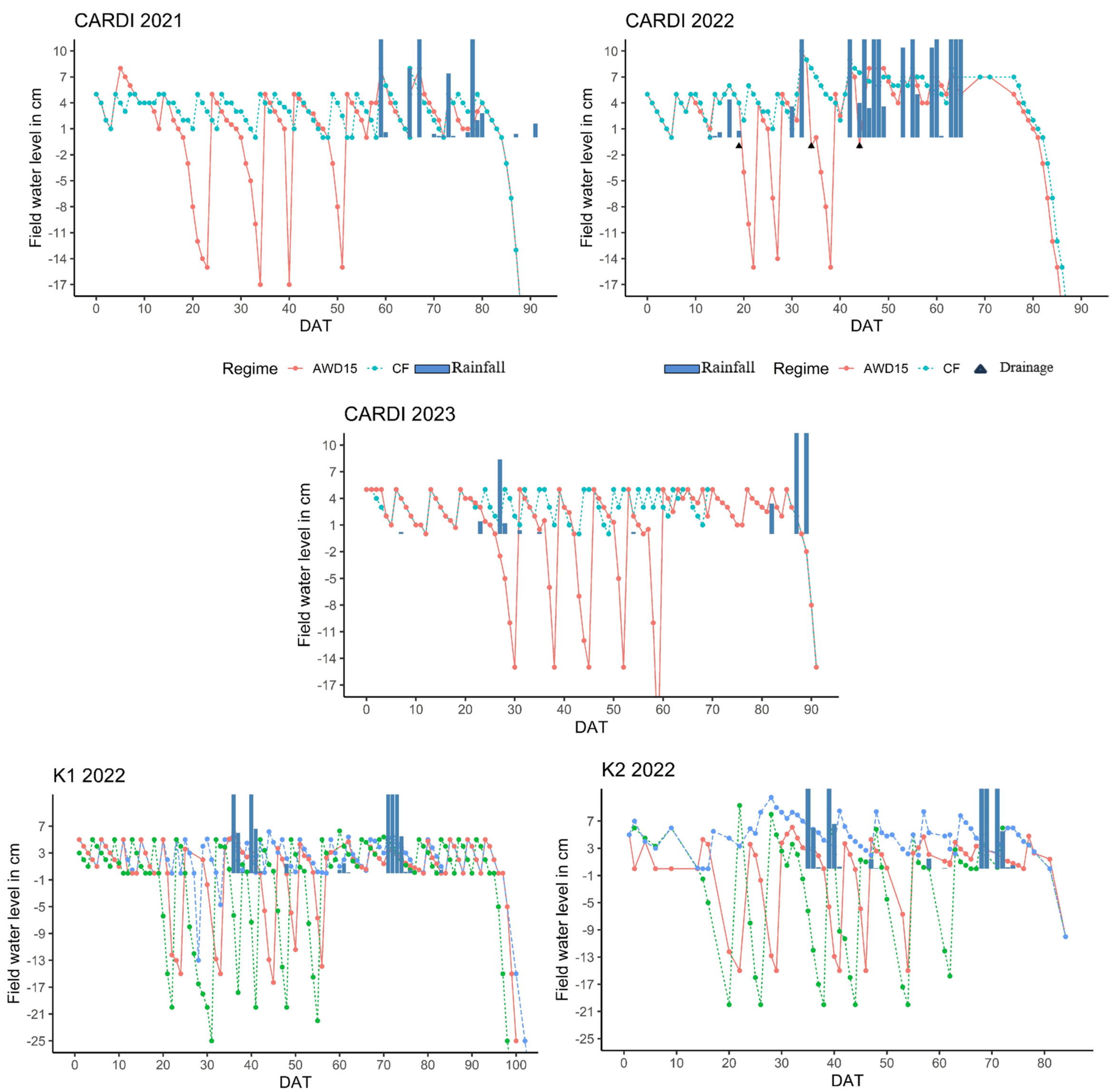

Fig. 3 Typical water level management chronologically for both AWD and CF

Yield Component was not significantly impacted by environmental parameters such as soil, variety, and regime. Latent variables like Yield Component and Variety that were not significant were removed to increase the model's fitness. The final model for CARDI is shown in Fig. 5.

In the final model for CARDI, all factor loadings for all Yield indicators were higher than 0.5 with AVE = 0.66, CR (Rho-a) = 0.85. This indicates that all the factor loadings satisfy the requirement for structural validity (Moeinaddini et al. 2020). The latent variables, Yield and WUE were well explained by Soil and Regime (R^2 = 53.5% and 82.2%, respectively). The results indicate that water management had no significant impacts on yield, but it did improve the WUE significantly at $p < 0.01$ with a path coefficient of 0.98. Latent variable Yield and Regime directly influenced WUE. Soil had no direct effect on WUE. However, it influenced the yield and indirect effect on WUE with a path coefficient of 1.36 and 0.41, respectively.

Effect of soil properties and water management on Grain yield, and WUE

Figure 6 displayed indicators from the PLS-SEM model that described the performance of AWD under various soil conditions, including grain yield, HI, panicle/m^2, and WUE. In both sites, grain yield, HI, and panicle/m^2 of rice grown under AWD were not significantly different from those grown under CF. Site B was significantly more productive than Site A. Average yield, HI, panicle/m^2, and WUE of Site B were found to be 56%, 40%, 40%, and 43% higher than

Table 3 Soil characteristics of the four experimental fields (CARDI and Kampong Thom)

Year/Site	Layer	Depth (m)	Texture	Bulk density	PWP (V%)	FC (V%)	SAT (V%)	Ksat (mm/d)
2021–2022 CARDI Site A	1	0–0.2	Sandy loam	1.76 ± 0.04	6.64 ± 3	17.79 ± 3	34.8 ± 4.3	16 ± 4.7
	2	0.2- 0.5	Sandy loam	2.07 ± 0.11	12 ± 3.5	21.70 ± 5.8	34.79 ± 5.5	2.5 ± 1 .6
	3	0.5- 0.8	Loam	2.03 ± 0.03	12.22 ± 4	23.14 ± 7.9	35.92 ± 02	1.5 ± 1.2
2023 CARDI Site B	1	0–0.3	Sandy loam	1.87 ± 0.14	9.6 ± 2.8	29 ± 2	39 ± 1	169 ± 97
	2	0.3 – 0.4	Sandy loam	1.89 ± 0.1	10 ± 2.8	23 ± 1	36 ± 4	5.5 ± 1.2
	3	0.4–0.8	Sandy loam	1.69 ± 0.1	9.5 ± 1.5	22 ± 3	37 ± 4	2.4 ± 1.9
2022 KTM K1	1	0–0.25	Sandy loam	1.71 ± 0.04	10.50 ± 0.6	19.62 ± 1.2	28.22 ± 3	100 ± 47
	2	025–0.5	Sandy loam	1.83 ± 0.03	12.27 ± 4.5	20.05 ± 3.1	27.54 ± 2.6	80 ± 40
	3	0.5–0.8	Sandy loam	1.73 ± 0.04	18.21 ± 2.5	24.85 ± 2.2	32.31 ± 0.3	25 ± 5
2022 KTM K2	1	0- 0.2	Sandy clay loam	1.72 ± 0.08	20.11 ± 2.1	28.73 ± 1	32.24 ± 0.6	6.68 ± 2.6
	2	0.2–0.3	Clay loam	1.70 ± 0.05	20.86 ± 0.4	28.77 ± 4	32.64 ± 1	1.3 ± 0.3
	3	0.3–0.8	Clay	1.70 ± 0.07	20.11 ± 2.3	21.17 ± 1.6	41.14 ± 3.7	10 ± 0.01

Layer, depth, texture, bulk density, permanent wilting point (PWP) in volumetric moisture content (V%), field capacity (FC), saturation (SAT) and saturated conductivity (Ksat)

Table 4 Number of days after transplanting (DAT) to flowering and maturity of rice grown under AWD15 and CF at both sites at CARDI from 2021 to 2023

Year/Site	SP	SK	CAR	OM				
	CF	AWD	CF	AWD	CF	AWD	CF	AWD
2021-2022 CARDI Site A								
Flowering	68 ± 1	67 ± 1	63 ± 1	63 ± 1	54 ± 1	55 ± 2	50 ± 1	50 ± 1
Maturity	98 ± 1	97 ± 1	93 ± 1	93 ± 1	84 ± 1	85 ± 1	80 ± 1	80 ± 1
2023								
CARDI Site B								
Flowering	62	63	69	69	61 ± 1	64	59	59
Maturity	92	93	99	99	91 ± 1	94	89	89

Table 5 Number of days after transplanting (DAT) to flowering and maturity of rice grown under AWD20, AWD15, and CF in Kampong Thom in 2022

Year/Site	CAR15		
	AWD15	AWD20	CF
2022 KTM *K1*			
Flowering	70 ± 3	70 ± 3	68.25 ± 2
Maturity	100 ± 3	100 ± 3	98.25 ± 2
2022 KTM *K2*			
Flowering	59 ± 2	56 ± 1	58 ± 2
Maturity	89 ± 2	86 ± 1	88 ± 2

those of Site A, respectively. Yields of Site B varied from 2.3 to 6.2 tons/ha while yields of Site A varied between 2.2 to 3.5 tons/ha.

At Site A, WUE ranged from 0.35 to 0.56 kg/m^3, while at Site B, it varied from 0.25 to 0.77 kg/m^3. WUE of AWD15 were significantly higher than CF for both sites. On average, WUEs of AWD15 of Site A and Site B were 40% and 19% higher than those under CF, respectively.

Effect of variety on yield, yield component and WUE at CARDI

When the three experimental data sets were merged in PLS-SEM, the effect of variety on grain yield was negligible. This was because varietal differences in grain yield were significant at Site B but not at Site A. At Site B, OM had the greatest grain yield; whereas, SK had the lowest. At Site B, OM produced, on average, 26%, 30%, and 116% higher yields than SP, CAR, and SK regardless of water treatment, respectively. In addition, OM demonstrated greater WUE under full and AWD15, followed by CAR15 for both sites. Aboveground biomass and plant height were insignificant and inconsistent across variety, location, and water treatments.

When it comes to filled spikelets in both regimes, variety OM ranked at the top. The number of filled spikelets was consistent across varieties, locations, and regimes (with the exception of AWD15 at site A). Number of spikelets per panicle was similar across varieties, locations, and regimes (except in the CF of site B). Except

Table 6 Average total water input of rice grown under AWD20, AWD15, and CF at CARDI from 2021 to 2023 and at Kampong Thom during 2022. Irrigation water included 50 mm for land preparation for all treatments

Year/Site	Water regime	Irrigation (mm)	Irrigation frequency (time)	Rainfall (mm)	Saved water (%)
2021 CARDI Site A	CF	765 ± 25	15	144	31%
	AWD15	480 ± 25	10	144	
2022 CARDI Site A	CF AWD15	465 ± 25	9	459	11
		363 ± 25	4	459	
2023 CARDI Site B	CF	915 ± 22	18	82.7	20
	AWD15	713 ± 22	14	82.7	
2022 KTM K1	CF	1113 ± 74	22.25	149	
	AWD15	863 ± 41	17.25	149	20
	AWD20	813 ± 55	16.25	149	24
2022 KTM K2	CF	613 ± 22	12.25	149	
	AWD15	475 ± 56	9.25	149	18
	AWD20	445 ± 22	8.25	149	22

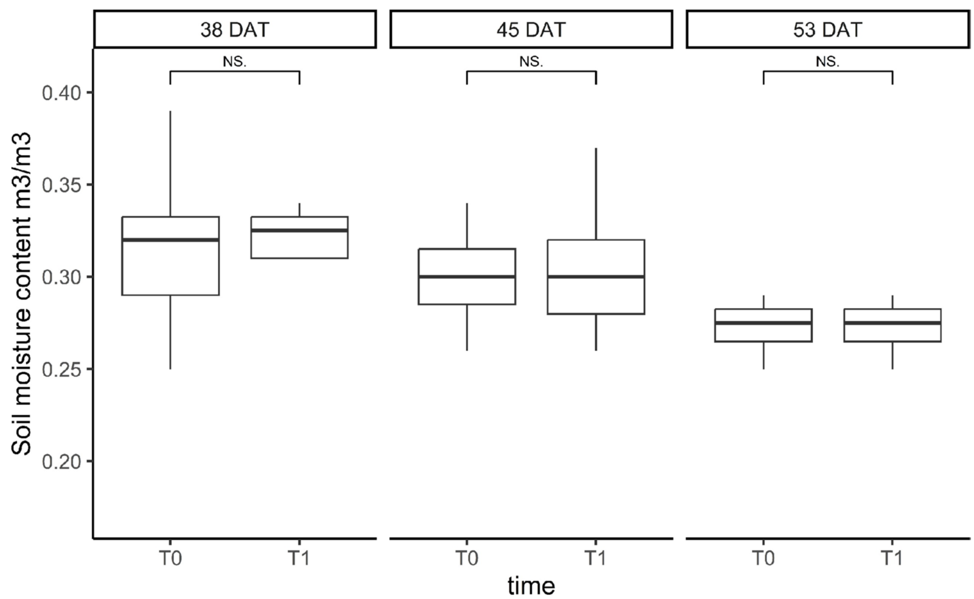

Fig. 4 Volumetric SMC of AWD15 plots at Site B (CARDI) (T0: one hour before and T1: one hour after irrigation) during the growth season 2023. Student t-tests at significant differences ($P < 0.05$) were used to assess the significant differences between T0 and T1

for plant height, variety had no significant impact on root depth, HI, or number of panicles per m^2.

Feasibility of mild AWD

In Kampong Thom, the average grain yields varied from 3.1 to 4.1 tons/ha in K1 and between 2.6 to 5.1 tons/ha in K2 (Table 7). Results of ANOVA demonstrated that soil had an influence on WUE, biomass, Panicle number/m^2, plant height, and number of spikelets per panicle but not on the rest of the variables. Rice grown at K2 produced greater WUE, plant height, and number of spikelets per panicle than K1, while at K1, biomass and Panicle number/m^2 were greater than K2. The use of AWD15 and AWD20 did not significantly reduce the grain yield of CAR15 in both sites. WUE in K2 were significantly higher than those in K1. In K1, the average WUE under the three treatments ranged from 0.3 to 0.38 kg/m^3, while in K2, it ranged from 0.5 to 0.88 kg/m^3. However, there was no significant difference in WUE between the regimes in K2 (sandy clay loam), which was opposite to the findings in K1 and the two sites at CARDI (Sandy loam), where the WUE of AWD15 was significantly higher compared to those under CF. Panicle number/m^2 in K1 was significantly higher than in K2. Among all indicators, only HI that were affected by the water regime. According to pairwise test, HI in AWD20 was significantly higher than CF and AWD15.

In AWD15 and AWD20, HI was slightly but significantly greater than in CF in K1. CF had the most spikelets per panicle, followed by AWD15 and AWD20 in K2. Root depth,

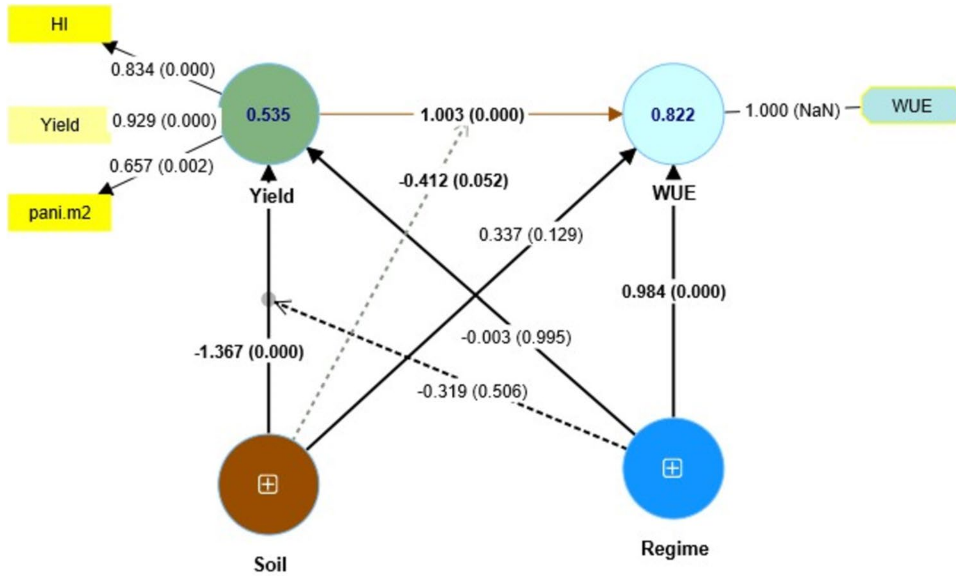

Fig. 5 Final PLS-SEM model diagram, shows the relationship between each variable and the distribution of yield and WUE at CARDI from 2021 to 2022. The circles represent latent variables and the rectangles represent manifest variables. Arrows represent paths, where path coefficient and p value are displayed adjacent to arrows (significant values are bold). Model R^2 inside the latent variables

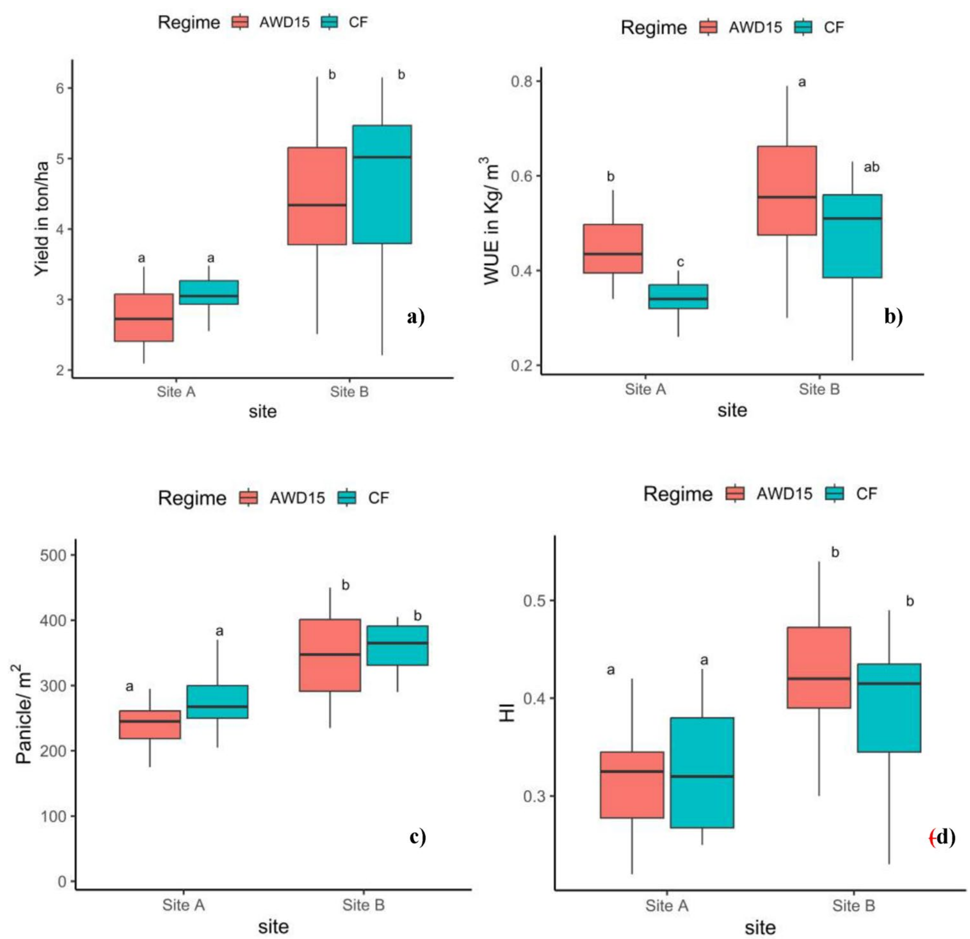

Fig. 6 Boxplot of grain yields (tons/ha) (a), WUEs (kg/m^3) (b), panicle number per m^2 (c), and Harvest index (d), at rice harvests of the two sites at CARDI from 2021 to 2023. Grain yields are shown for 14% moisture content equivalent. Different lowercase letters represent significant differences ($P < 0.05$) among treatment and location mean, analyzed by two-way ANOVA

percentage of filled spikelets, and number of filled spikelets were consistent in all regimes and in both soil types. The interaction between soil and water was observed only on biomass and the number of spikelets per panicle.

Effect of AWD on the growth of Canopy cover and biomass in all locations

The interaction of the water regime with soil and variety did not significantly affect time series biomass and CC in all

Table 7 Grain yield, WUE, biomass, panicle.m^{-2}, plant height, percentage of filled spikelet, number of filled spikelet, Harvest index, number of spikelet per panicle and root depth of variety "CAR15" under continuous flooding (CF) and alternate wetting and drying (AWD15 and AWD20) irrigation at Kampong Thom Province during 2022

Site/ regime	Grain yield (t ha^{-1})	WUE (kg m^3)	Biomass (t ha^{-1})	Paniclem^{-2}	Plant Height (cm)	Filled spikelet (%)	Number of filled spikelet	HI	Spikelet panicle^{-1}	Root depth (cm)
K1										
CF	3.64 a	0.29 a	13.46 a	320 a	93 a	76 a	292 a	0.43 a	384 a	11 a
AWD15	3.8 a	0.38 ab	11.03 a	273 a	92 a	77 a	341 a	0.45 ab	443 a	11 a
AWD20	3.28 a	0.32 a	11.58 a	313 a	89 a	73 a	292 a	0.45 b	406 a	12 a
Mean	3.57	0.33	12.17	302	91	75.17	308	0.44	411	11.33
K2										
CF	4.23 a	0.56 a	7.52 a	250 a	104 a	72 a	406 a	0.45 a	560 a	11 a
AWD15	3.87 a	0.62 a	8.39 a	265 a	102 a	71 a	358 a	0.43 a	499 ab	11 a
AWD20	3.31 a	0.56 a	8.91 a	268 a	100 a	81 a	305 a	0.47 a	381 b	10 a
Mean	3.80	0.58	8.27	262	102	74.50	356	0.45	480	11.21
ANOVA										
Regime (R)	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
Soil (S)	ns	**	**	*	**	ns	ns	ns	*	ns
R*S	ns	ns	*	ns	ns	ns	ns	ns	*	ns

Within a column for each location, means followed by the same letter are not significantly different according to LSD (0.05). Lower-case letters indicate comparisons among three water treatments. In the ANOVA, ns means nonsignificant ($P > 0.05$), * means $P < 0.05$, ** means $P < 0.01$

locations. From the vegetative stage to the ripening stage, biomass and canopy cover increased independently regardless of water regimes. According to Figs. 7 and 8, the mean canopy cover increased during the reproductive stage, from weeks 6 to 10, and then started to decline at CARDI in week 10 and KTM in week 11. In contrast, biomass rose until it reached its maximum before being harvested.

Soil and variety significantly influenced CC. Compared to the other varieties, which had CC values that were comparable, CAR15 had the greatest CC. Compared to Site A and K1, CC of Site B and K2 was noticeably higher. In both treatments, the maximum percentage of CC for CAR15, OM, SK, and SP was 60%, 47%, 50%, and 52%.

Discussion

Water saving, yield, and WUE of safe AWD

Three experiments were conducted at CARDI to investigate the potential benefits of AWD15 and the influence of soil and variety. The results indicate that there were no

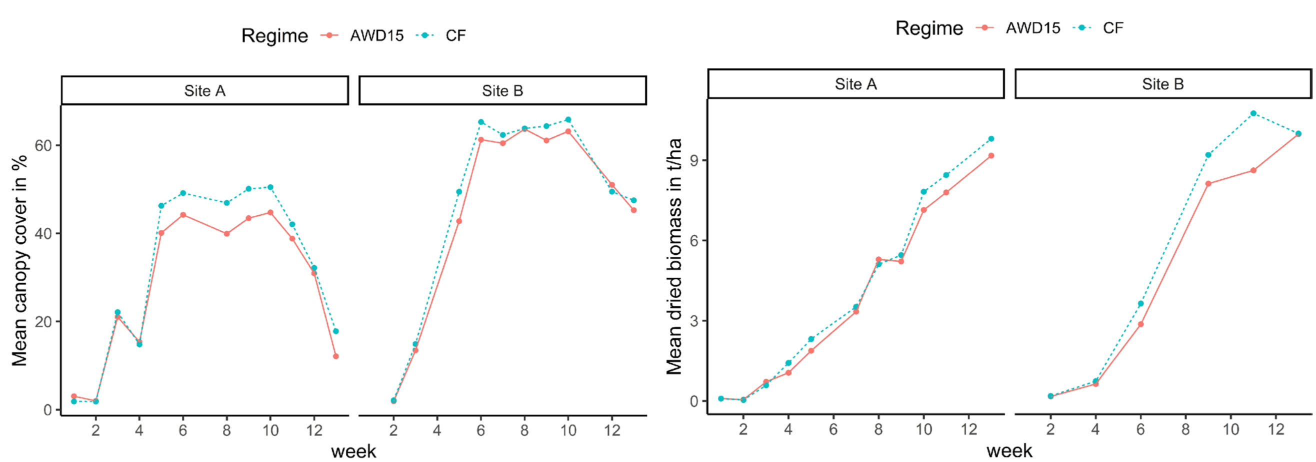

Fig. 7 Time series growth of canopy cover and dried biomass of rice grown under CF and AWD15 for both sites at CARDI (mean values) from 2021 to 2023

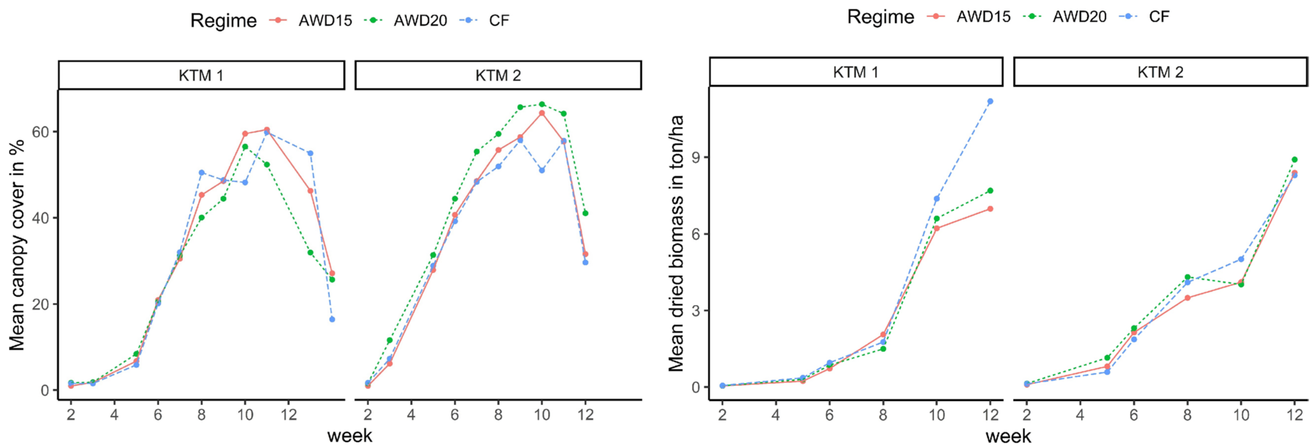

Fig. 8 Time series growth of canopy cover and dried biomass grown under CF and AWD15 for both sites at Kampong Thom Province (mean values) during 2022

significant differences between the rice paddies under the two water management systems regarding grain yield, yield components, harvest index, and root growth for all tested soil properties.

The possible explanations for this outcome are twofold: (1) our rice did not experience water stress during 3–4 days of water depletion when the water level dropped below -15 cm. The AWD cycle in this research ranged from five to ten days, consistent with what Sandhu et al. (2017) reported. (2) stopping AWD before the flowering stage did not affect the yield formation. Carrijo et al (2017) reported that AWD is safe when the field water level is $\leq$ 15 cm, soil water potential is $\geq$ –20 kPa, and when applied only during the vegetation stage instead of the whole season. When it came to rice phenological stages, applying AWD at the reproductive stage resulted in lower yields than applying it at the vegetative stage (Carrijo et al. 2017; Mote et al. 2018). However, opposite to the finding of Pascual and Wang (2017), our grain yields were not reduced as a result of the overlap between the AWD drying cycle and the panicle. Our findings support previous studies by Lampayan et al (2015) and Yao et al (2012) that found AWD15 can save water and maintain yield. However, these results contradict the findings of Sanhu et al. (2017), who conducted a previous study at the same location and found that yields increased by 6–8% with AWD15 using different varieties. The mean grain yield in the rice paddies under both treatments was 3.42 $\pm$ 1.1 tons/ha, which is still lower than the reported grain yields of 3.8 to 8 tons/ha in the above studies.

Furthermore, AWD15 was found to save water by an average of 20 to 31% during completely dry seasons and 11% when rainfall occurred. This finding aligned with Yao et al. (2012) and was higher than previous studies by Sanhu et al. (2017). However, these savings were still lower (8 to 30%) than those reported in studies by Lampayan et al. (2015), Arai et al. (2021), and Xiao et al. (2021). The average WUE was 0.43 $\pm$ 0.12 kg/m^3, ranging from 0.2 to 0.8 kg/m^3, in the AWD15 treatment. WUE in this study was lower than that of other studies due to the lower grain yields observed. It is also important to note that the amount of water saved in this study did not account for the infiltration rate during irrigation due to technical limitations. The water content sensors are reassuring regarding the infiltration rate, which is limited during the irrigation activity.

Possibility to extend the AWD threshold

Another two experiments were carried out at Kampong Thom in order to explore the possible advantages of AWD20. We tested three different water regimes, namely CF, AWD15, and AWD20 while using only one rice variety, which was CAR15. The findings demonstrated that under the sandy loam and sandy clay loam rice soils in the experimental sites, lowering the threshold level of AWD by up to 20 cm remained safe. The results of the study support the previous recommendation by Bouman et al. (2007) and findings from Wiangsamut (2010) that implementing AWD is "safe" in terms of yield, as there is no penalty in yield but a significant reduction in water usage, as long as fields are irrigated when the water level falls to 15–20 cm below the ground surface. In addition, Carrijo et al. (2017) also reported that the interaction between soil property and water management was more critical only when applying severe AWD.

CAR15's grain yield, harvest index, root depth, and yield components were found to be more significantly affected by soil conditions rather than the regime, similar to the findings observed at CARDI. The average yield for both locations was 3.68 $\pm$ 0.6 tons/ha, with a range of 2.7 to 4.6 tons/ha. Compared to CF, total water inputs were significantly reduced by 18–20% in AWD15 and by 22–24% in AWD20, while yields remained the same. Safe and mild AWD did not significantly differ in total water input, which is consistent with findings by Sudhir-Yadav et al. (2010) and Lampayang et al. (2015). In K1 (sandy loam), but not in K2 (sandy clay loam), WUE was significantly higher in the AWD treatments than in CF. The WUE of AWD15 was the highest among the AWD treatments at K2. No differences in aboveground biomass and CC were observed among water treatments at different stages of the crop.

Influence of variety and soil property on AWD

The varietal effect was not significant overall. However, among the four chosen varieties, OM and CAR15 were suggested as having stable yield and WUE because they resist regime and geographic changes.

The large variability of grain yields, yield components, HI, and WUE of rice under both treatments was caused by differences in the soil properties. For instance, Site B was the most productive; its yields were 56%, 28%, and 21% higher than those of Site A, K1, and K2. However, the response of rice to soil property in terms of yield component and HI was not consistent. In our finding, yield components such as biomass, number of filled spikelets, plant height, and number of spikelets per plant were all impacted by soil at KTM. However, only HI and panicle number per m^2 were influenced by soil at CARDI. Effective root depth was always consistent across regimes and locations.

Additionally, the study found that AWD15 and AWD20 treatments improved WUE over CF on sandy loam soil. Soil texture, however, affects the duration of AWD cycles and the number of irrigation cycles. In this study, the value of Ksat at each location is negatively correlated with the total amount of irrigation. As a result, K1 and Site B, having higher values of Ksat, required more water and irrigation cycles for both CF and AWD. In addition, as clay soil (K2) consumes less water, its WUE is greater than that of sandy loam (CARDI and K1) under both CF and AWD. Our finding supports the finding of (Linquist et al. 2015) who pointed out that clayey soil has lower percolation losses and takes longer to reach the target soil moisture potential. Conversely, sandy loam soils have higher percolation losses and reach the drying stage faster (Sharma et al. 2002). This is because WUE is the ratio of grain yield over total irrigation water; thus, soil that requires less water will have greater WUE among varieties having comparable grain yield. Though clay soil's WUE was higher than that of sandy soil, our study found that clay soil's WUE in AWD did not improve over CF. This was because we observed that K2 (clay soil) required less irrigation, and the amount of water saving was small to create a difference between WUE in CF and AWD.

Conclusion

The finding demonstrates that safe and moderate AWD as a water-saving technique is suitable for dry season rice growing on sandy loam and sandy clay loam. A water depletion of -15 to -20 cm in the subsoil was found to be acceptable to maintain yield, while also achieving water savings of 10–30%. Additionally, the improvement in water use efficiency (WUE) was observed only in sandy loam soil. It is important to note that the success of AWD application may depend on the soil's saturated conductivity (Ksat) and grain yield, regardless of its texture. To achieve optimum yield and WUE in the AWD system, it is recommended to focus on improving soil nutrition and selecting high-quality rice varieties. However, it is important to note that this study was conducted on a field experimental scale, and further research is needed to assess the generality of these findings across different soil types and within a larger scale. Nonetheless, the results indicate that AWD has significant potential as a water-saving technique for rice cultivation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10333-024-01012-5.

Acknowledgements We are particularly grateful to Pascal Jouquet for his assistance with the statistical analysis, PEAR LAB and Soil LAB of ITC to provide space and consumables. This work is part of the PhD of Chan Arun Phoeurn, under a double degree program between the Institute of Technology of Cambodia and the University of Liege, Belgium. This study was funded by the Cambodia Higher Education Improvement Project (Credit No. 6221-KH).

Funding Ministry of Education, Youths and Sports, the Cambodia Higher Education Improvement Project (Credit No. 6221-KH),Chan Arun Phoeurn

Declarations

Conflict of interests The authors declare that they have no conflict of interest.

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