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Research article

Effect of alternate wetting and drying technology on growth, yield and physiological responses of glutinous rice in northeast Thailand

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Abstract

Importance of the work: Alternate wetting and drying (AWD) is a water-saving technique essential for rice cultivation under the current climatic situations where high water productivity is a concern.

Objectives: To investigate the effects of moderate AWD application and CF (continuous flooding) on the growth, yield, grain quality and physiological responses of the traditional, local Leenok and the modern, improved RD22 glutinous rice varieties.

Materials and Methods: A field study was used, with 3 × 5 m rice paddy plots and a 2 × 2 factorial randomized complete block design involving two levels of water—continuous flooding (CF) and moderate stress (AWD25)—as Factor A and two glutinous rice varieties as Factor B.

Results: Compared to CF, AWD25 had a better number of tillers, better values for all yield and yield components (number of panicles per hill, panicle length, number of grains per panicle, number of filled grains, 1,000-grain weight, yield, straw yield and harvesting index. However, AWD25 had a lower filled grain percentage but a higher broken grain percentage than CF. Compared to CF, AWD25 had greater values for the relative growth rate (RGR), specific leaf weight (SLW) and leaf area index (LAI). However, the leaf chlorophyll a content was higher under CF, whereas the carotenoid content was greater under AWD25. Leaf total nonstructural carbohydrates and grain sucrose were higher under CF, while the grain starch percentage was higher under AWD25 and Leenok had a greater accumulation of grain starch and sucrose than RD22 rice. Water use under AWD25 was 27.83% less than for CF, while the water use efficiency was 31.43% better than for CF. Combination effects existed in many responses.

Main finding: AWD25 had better growth, yield and water productivity than CF. Leenok performed better than RD22 under AWD25 than under CF.

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Introduction

Rice, both non-glutinous rice (*Oryza sativa* L.) and glutinous rice (*Oryza sativa* var. *glutinosa*), is one of the most important staple food crops for people globally as it is consumed by almost one-half of the world's population, especially in Asia (Schneider and Asch, 2020). It is widely cultivated across Asia and other parts of the world with different varieties or subspecies being planted in different growing regions (Gadal et al., 2019). Therefore, it has played a prominent role in the world's food security and sustainability from the past to the present (Takayoshi et al., 2016). Glutinous rice is a very important food crop, particularly for people in Southeast Asian countries, including Thailand, Laos, Indonesia and Malaysia (Lei et al., 2021; Yarwati et al., 2023). It is consumed as the main staple or as one of the primary ingredients in local sweets and desserts (Perdani et al., 2018). The main difference between both these types of rice is based on in the amount of grain starch, with glutinous rice containing less (< 5%) or almost no amylose, while having a higher amylopectin content and antioxidant capacity than the regular (non-glutinous) rice (Setyaningsih et al., 2015).

As rice cultivation requires a large amount of water for production and water availability is increasingly fluctuating due to extreme climatic conditions due to global warming, water consumption has become a limiting factor affecting rice production, especially for irrigated rice production systems, where it has been reported that about 80% of the total irrigated freshwater resource is used by traditional continuous flooding (CF) for rice production in Asia (Bouman and Tuong, 2001). Horie (2019) used a modeling technique that projected extreme climate fluctuations, dominated by either drought or flooding incidence, would (due to global warming) have enormous impacts on the uncertainty of future food security in Asia. In addition, rice cultivation and production have been predicted to reduce by 51% during the next century due to global warming, with rice production itself contributing about 10–14% of total global greenhouse gas emissions and 18% of the total methane emitted from paddy rice fields (Hussain et al., 2020). Therefore, it is important and practical to adapt water saving technology for rice cultivation to reduce the impact of global warming, while at the same time, maximizing the growth and yield of the rice to ensure sufficient and sustainable food supply for the human population.

Alternate wetting and drying (AWD) is an intermittent irrigation technique where the water levels are managed and monitored through a suitable wetting and drying cycle during the growing period of the rice, without having a negative impact on growth and yield (Yang et al., 2017). This rice production practice has been introduced and suggested for rice production in many areas, since it has been shown that appropriate water management under AWD results in many beneficial advantages for optimal rice production, especially high water productivity, as well as reducing water use by up to 30% and reducing methane emissions by 48% without affecting yield (Zhang et al., 2012; Takayoshi et al., 2016; Carrijo et al., 2017; Majeed et al., 2017; Carrijo et al., 2018). Under moderate water stress conditions, rice plants are able to adjust their molecular, biochemical, physiological, morphological and agronomic traits to cope with both water stress (deficit) or excess water (flooding) conditions in order to optimize growth and yield (Pandey and Shukla, 2015). Physiological responses of the rice plants have been reported such as photosynthesis, a source and sink relationship and other responses associated with alteration of growth above ground and below ground (Ishihara and Saito, 1983; Zhu et al., 2017; Carrijo et al., 2018; Rodrigues et al., 2019; Ramegowda et al., 2020; Xu et al., 2020).

Different responses under different levels of water stress and different growing conditions have also been reported in various hybrid and traditional rice varieties (Yao et al., 2012; Zhang et al., 2012; Kumar et al., 2017). However, more research is required on the impacts of AWD on different rice varieties under different growing areas with different geographical conditions, to obtain more extensive knowledge to support the practical adaptation of this water-saving rice production technology. Based on the literature review, there has been only limited study on the effect of AWD on glutinous rice; thus, more research on the potential application of AWD for the glutinous rice production is required. Therefore, the current research aimed to examine the growth, yield and physiological responses of glutinous rice to water deficit stress conditions, to assess both the positive and negative impacts of CF and moderate AWD under field conditions, especially in the sandy loam soils in northeast Thailand. The data obtained should be useful for policy makers to adapt water management practices for glutinous rice production in the region.

Materials and Methods

Site information and experimental setup

The experiment was conducted in an experimental field of the Faculty of Agriculture, Ubon Ratchathani University, Ubon Ratchathani, Thailand during December 2021–April 2022.

During the experimental period (2021–2022), data from the Northeastern Meteorological Station, Ubon Ratchathani province showed that the average precipitation was 4.62 mm and the minimum and maximum temperature ranges were 14.5–20.5°C and 31.1–36.1°C, respectively, with relative humidity in the range 63–72%. The site was mainly a sandy loam soil (0.45% organic matter, pH 6.42), which is typical of soils in northeast Thailand (Taparat and Soontorn, 2016).

The study applied a 2 × 2 factorial layout based on a randomized complete block design with the water level as Factor A and the rice variety as Factor B. For Factor A involved two levels of water management regimes: continuous flooding (CF; keeping the water level at 5 cm above ground level all times) and an alternate wetting and drying practice (AWD) at a moderate stress level (AWD25), where the water was re-flooded into the paddy plot and the water level reached 25 cm below ground level. Factor B involved two varieties of glutinous rice: Leenok (a local variety) and RD22 (a modern and improved variety). A series of 3 × 5 m rectangular plots was prepared with contours 0.2–0.3 m high and 0.3–0.4 m wide. Thick plastic sheeting was installed 1 m underground between the contours on all four sides of each plot to prevent any interchange of overflow water between the plots. Each treatment consisted of four replications (with one plot as one replication), resulting a total of 16 plots for the experimental units.

Plant preparation and transplanting

Seeds of the Leenok and RD22 glutinous rice varieties were soaked in water for 24 hr and subsequently kept at ambient conditions for another 24 hr to allow initial germination, followed by sowing into seedling trays filled with a soil mixture (3–5 seeds per pit). At 20 d after sowing, strong and healthy seedlings were selected and transplanted into each experimental plot (25 cm × 25 cm spacing) with one seedling per hill, producing a total of 240 hills per plot (12 rows with 20 hills per row). N-P-K chemical fertilizer was applied at 15 day after transplanting (DAT), consisting of 46-0-0, followed by an application at 30 DAT, consisting of 16-16-8, at a total of 562 g per plot.

Water level management

The levels of water in all experimental plots were maintained at about 5 cm above the soil surface for 15 DAT to allow the seedlings to establish, before applying each treatment described above. For the CF treatment, the water level was regularly maintained at 5 cm above the ground surface. For the AWD25 treatment, a piece of PVC pipe (diameter approximately 6.5 cm; length 30 cm, with 40 drilled holes) was buried 25 cm below ground level in each of the AWD25 experimental plots for the observation of the groundwater level. When the water level decreased to 25 cm below ground, the water level was refilled in the plot to 5 cm above the ground surface. These cycles were repeated and monitored until the rice plants reached the full growth and the panicle initiation stage (60 DAT) to avoid any negative impact of water deficit on the growth and yield of the rice plants, since any water limitation beyond these levels would affect the yield capacity of the rice, as reported above.

Measurement of crop growth, yield, yield components and grain quality

Crop growth data (plant height and tiller number per hill) were collected from 10 randomly selected plants from each plot at 15 DAT, 30 DAT, 45 DAT, 60 DAT and 100 DAT.

Yield and yield components were collected at harvest (120 DAT), consisting of panicle number, panicle length, total grains per panicle, filled grains per panicle, 1,000-grain weight, grain yield, straw yield and harvest index (HI). The grain yield (in kilograms per hectare) and HI were calculated according to Equations 1 and 2, respectively:

$$\text{Grain yield (kg/hectare)} = [(100\text{-MC}) \times (a)\ \text{g} \times 10{,}000\text{m}^2] \times [(100\text{-}14) \times 1{,}000\ \text{g} \times (b)\ \text{m}^2]^{(-1)} \quad (1)$$

Where MC is the grain moisture content as a percentage, a is the weight of the sample in grams and b is the sample area in sample hill.

$$\text{HI} = \text{Grain yield} \times (\text{Grain yield} + \text{Straw yield})^{-1} \quad (2)$$

Where all yields are measured in grams.

Rice grain quality

The numbers of full and broken grains were quantified as follows. After air-drying for 7 d after harvesting, the rice grains were collected and the moisture content was reduced to 14%. A random sample of 100 g was taken and de-husked and processed in a rice mill (NW 150; Natrawee Technology Co.; Thailand). The full and broken grains were separated, weighed and the percentages of full and broken grains were determined.

Leaf total nonstructural carbohydrate

The amount of total nonstructural carbohydrate (TNC) of the leaf was measured at 60 DAT using the acid extraction method, according to Yoshida et al. (1976). Each leaf sample was dried in a hot-air oven at 70°C for 72 hr. Next, 50 mg of the finely ground leaf sample was placed into an Erlenmeyer flask (100 mL) and 40 mL of H2SO4 (0.2 N) was added into the flask before incubating in a water bath at 100°C for 1 hr. After cooling at room temperature, the sample was passed through Whatman filter paper # 42 and the pH was adjusted to 6.9–7.2 with NaOH (0.1N). The final volume was adjusted to 50 mL with distilled water and used for TNC quantification based on Nelson's reducing sugar procedures (Reference). The absorbance of the sample was measured using a spectrophotometer (UV1240; Shimadzu; Japan) at 540 nm and a standard curve of D-glucose (based on 0.02 mg/L, 0.04 mg/L, 0.06 mg/L, 0.08 mg/L, 0.10 mg/L and 0.12 mg/L) was used for TNC calculation and expressed as milligrams per gram dry weight (DW), according to Xin et al. (2021).

Grain sucrose

The sucrose content of the grains was quantified after the grain sample had been dried in a hot-air oven at 60°C for 36 hr and the ground into fine powder with a mortar and pestle. A 50 g sample was placed into a test tube (100 mL) and 10 mL of distilled water (diH_2O) was added to the sample before shaking in boiling water for 15 min. After cooling at ambient temperature, the mixture was passed through Whatman filter paper # 1 and the final volume was brought up to 50 mL with diH_2O. An aliquot of 1 mL of the filtrate was used for sucrose quantification by adding 1 mL of phenol solution (5%) and 5 mL of concentrated sulfuric acid. The assay sample was mixed and incubated at ambient temperature for 30 min before measuring the absorbance at 485 nm using a spectrophotometer (UV1240; Shimadzu; Japan). The amount of grain sucrose was calculated according to the standard curve and expressed as milligrams per gram DW (Chen et al., 2023).

Grain starch

A finely ground rice grain sample (50 mg) was placed into a 100 mL test tube and 10 mL of diH_2O was added before boiling for 15 min. After cooling at room temperature, the sediment was filtered with sheet cloth into a beaker. The resulting filtrate was adjusted to 10 mL with diH_2O, and 13 mL of $HClO_4$ (52%) was added and incubated with shaking for 20 min. Then. the mixture was filtered through Whatman filter paper # 1 and the final volume was adjusted to 50 mL with diH_2O. An aliquot of 0.1 mL sample was brought up to 1.0 mL solution with diH_2O in a 10 mL test tube for assay and 3 mL of anthrone reagent (0.2%) and mixed well. The assay sample was kept in boiling water for 3 min and then immediately placed in ice water. After cooling, the absorbance of the sample was measured at a wavelength of 620 nm (UV-1240; Shimadzu; Japan) and the amount of starch was calculated using glucose as the standard. The starch content was expressed as milligrams per gram DW (Chen et al., 2023).

Measurement of crop physiological data

The leaf chlorophyll pigments were measured at 60 DAT. For quantification of leaf chlorophyll and carotenoid contents, an aliquot of 7 mL of dimethylformamide (DMF, 99.8%) was added to 0.2 g of leaf sample in a test tube and incubated in a water bath at 70°C for 90 min before cooling at room temperature. Then, the extract was passed through Whatman filter paper #42 and the final volume was brought up to a total of 10 mL with DMF. The absorbance of the sample was measured using a spectrophotometer (UV1240; Shimadzu; Japan) at the wavelengths of 664.2 nm, 648.6 nm and 470 nm, consecutively, and calculations for chlorophyll a (Chl a; Equation 3), chlorophyll b (Chl b; Equation 4), and carotenoids (Equation 5) were determined in milligrams per gram fresh weight (FW), according to Yoshida et al. (1976):

$$\text{Chlorophyll a} = [((12.7(A664)-2.69(A648)) \times V] \times [(1{,}000 \times W)]^{-1} \quad (3)$$

$$\text{Chlorophyll b} = [((22.9(A648)-4.68(A664)) \times V] \times [(1{,}000 \times W)]^{-1} \quad (4)$$

$$\text{Carotenois} = 1{,}000\,[A470+3.27(\text{Chl a} - \text{Chl b}) \times V] \times [(229 \times W)]^{-1} \quad (5)$$

Where W is the sample weight and FW is the fresh weight (both measured in grams), V is the solution volume (measure in milliliters) and Axxx is the wavelength (measured in nanometers).

The total chlorophyll (Chl a + Chl b) and chlorophyll a/b ratio were calculated using the results of Equations 3 and 4.

The relative growth rate (RGR) was measured in milligrams per gram per day based on the dry weight of the crops at ages 0 DAT, 30 DAT, 45 DAT and 60 DAT. The rice plant samples (3 hills/experimental unit) were collected, weighed and dried at 70°C for 48 hr before calculating the RGR, according to Equation 6:

$$RGR = (\text{Loge } W_2 – \text{Loge } W_1) \times (T_2 - T_1)^{-1} \quad (6)$$

Where W1 and W2 are the dry weights of the rice plants at 1st and 2nd harvest (measured in grams) and T1 and T2 are the 1st and 2nd harvest times (measured in days).

The specific leaf weight (SLW, measured in milligrams per square centimeter), which indicates the accumulated chlorophyll content per leaf area was measured at 0 DAT, 30 DAT, 45 DAT and 60 DAT. The rice plant samples (3 hills/experimental unit) were collected and measured for the leaf area and then annealed at 70°C for 48 hr before measuring the DW. The SLW was calculated according to Equation 7:

$$SLW = (\text{Leaf dry weight}) \times (\text{Leaf area})^{-1} \quad (7)$$

Where the weight is measured in grams and the area in square centimeters.

The leaf area index (LAI), which shows the relationship between leaf area and harvest area, was calculated at ages 0 DAT, 30 DAT, 45 DAT and 60 DAT and calculated, according to Equation 8:

$$LAI = (\text{Total leaf area}) \times (\text{Growing area})^{-1} \quad (8)$$

Where areas are measured in square centimeters.

Water use and water use efficiency

The total amount of water added to each plot was recorded during the experimental period and the water use was determined (in cubic meters per hectare) and the corresponding WUE of each treatment was calculated, according to Equation 9:

$$WUE = (\text{Grain yiela}) \times (\text{Amount of water use})^{-1} \quad (9)$$

Where the yield is measured in kilograms and the water use is measured in liters.

Statistical analysis

All data were subjected to analysis of variance based on a 2 × 2 factorial experiment in a randomized complete block design. Means separation between the two levels of each factor or between the treatment combination were done using the least significant procedure at the 95% confidence level (Gomez and Gomez, 1983) facilitated by the SPSS program (version 15; SPSS Inc.; USA). Correlation analysis (simple correlation) was carried out using Pearson's method between the yield and yield components and between the yield, grain sucrose, grain starch and leaf TNC of the rice plants under the different water management regimes.

Results

Rice plant growth

Overall, the height of the rice plants increased during the growing period (15–100 DAT) under both water management regimes and there was no significant difference in plant between the CF and AWD25 growing conditions (Table 1). The height of the RD22 variety was significantly ($p < 0.01$) greater than that of Leenok from 15 DAT until 60 DAT; but there was no difference in plant height at 100 DAT. The treatment combination of the water level and the variety was significant ($p < 0.01$) regarding plant height during 15–60 DAT, where the plant heights for RD22 rice under both CF and AWD25 was greater than for Leenok under the same growing conditions.

In addition, there was no significant ($p > 0.01$) effect for both the water level and the variety on the number of tillers per hill in the early growth stage (15 DAT); however, both factors were significant ($p < 0.01$) for the number of tillers per hill thereafter until the end of the experiment (100 DAT), with the rice plants grown under AWD25 having a greater number of tillers than those grown under CF (Table 2). It was also clear that the Leenok rice grown under AWD25 had a consistently greater number of tillers per hill than both the Leenok rice under the CF conditions and the RD22 rice grown under both water management regimes. The treatment combination analysis revealed that Leenok rice under AWD25 produced the highest number of tillers compared to CF and RD22 rice under both conditions.

Table 1 Height of rice plants (in centimeters) in each growth period (15 d, 30 d, 45 d, 60 d and 100 d after transplanting) for different factors: water management (A) and rice variety (B)

Factor	Days after transplanting				
	15 d	30 d	45 d	60 d	100 d
A (Water management)					
CF	27.47 ± 1.77	39.93 ± 1.34	48.64 ± 1.83	61.09 ± 2.87	86.28 ± 1.44
AWD 25	28.74 ± 4.02	41.44 ± 3.04	49.30 ± 4.14	63.10 ± 6.50	85.83 ± 3.27
F test	ns	ns	ns	ns	ns
B (Variety)					
Leenok	25.67 ± 1.77[b]	36.64 ± 1.34[b]	44.56 ± 1.83[b]	65.03 ± 2.87[b]	86.65 ± 1.44
RD 22	30.54 ± 4.02[a]	44.73 ± 3.04[a]	53.38 ± 4.14[a]	69.16 ± 6.50[a]	85.45 ± 3.27
F test	**	**	**	**	ns
A × B (Combination)					
Leenok × CF	23.96 ± 2.15[b]	36.78 ± 1.9[b]	44.25 ± 2.58[b]	53.83 ± 4.06[b]	86.40 ± 2.04
Leenok × AWD 25	27.37 ± 5.68[ab]	36.50 ± 4.31[b]	44.88 ± 5.85[b]	56.23 ± 9.19[b]	86.90 ± 4.63
RD22 × CF	30.96 ± 2.15[a]	24.09 ± 1.9[a]	53.03 ± 2.58[a]	68.35 ± 4.06[a]	86.15 ± 2.04
RD22 × AWD 25	30.11 ± 5.68[a]	46.38 ± 4.31[a]	53.73 ± 5.85[a]	69.98 ± 9.19[a]	84.75 ± 4.63
F test	**	**	**	**	ns
CV (%)	12.64	6.63	7.48	9.26	3.37

CF = continuous flooding; AWD25 = moderate water stress; CV = coefficient of variation.

Means (±SD) within each column with different lowercase superscript letters for each factor and growth period indicate significant differences at $p < 0.01$ (**); ns = no significant difference.

Table 2 Number of tillers per hill of rice plants at each growth stage (15 d, 30 d, 45 d, 60 d and 100 d after transplanting) for different factors: water management (A) and rice variety (B)

Factor	Days after transplanting				
	15 d	30 d	45 d	60 d	100 d
A (Water management)					
CF	2.00 ± 0.12	9.78 ± 0.34[b]	15.06 ± 0.80[b]	20.58 ± 0.55[b]	22.45 ± 0.60[b]
AWD 25	2.09 ± 0.28	11.55 ± 0.78[a]	17.43 ± 1.80[a]	23.23 ± 1.62[a]	25.46 ± 1.37[a]
F test	ns	**	*	**	**
B (Variety)					
Leenok	2.16 ± 0.12	13.33 ± 0.34[a]	17.66 ± 0.80[a]	23.34 ± 0.55[a]	23.85 ± 0.60
RD 22	1.93 ± 0.28	8.00 ± 0.78[b]	14.83 ± 1.80[b]	20.46 ± 1.62[b]	24.06 ± 1.63
F test	ns	**	**	**	ns
A × B (Combination)					
Leenok × CF	2.18 ± 0.18	11.68 ± 0.49[b]	14.65 ± 1.13[b]	21.23 ± 0.79[b]	20.63 ± 0.85[c]
Leenok × AWD 25	2.15 ± 0.40	14.98 ± 1.11[a]	20.68 ± 2.56[a]	25.45 ± 1.78[a]	27.08 ± 1.94[a]
RD22 × CF	1.83 ± 0.18	7.88 ± 0.49[c]	15.48 ± 1.13[b]	19.93 ± 0.79[b]	24.28 ± 0.85[b]
RD22 × AWD 25	2.03 ± 0.40	8.13 ± 1.11[c]	14.18 ± 2.56[b]	21.00 ± 1.78[b]	23.85 ± 1.94[b]
F test	ns	**	**	*	**
CV (%)	12.53	6.52	9.88	5.10	5.07

CF = continuous flooding; AWD25 = moderate water stress; CV = coefficient of variation.

Means (±SD) within each column with different lowercase superscript letters for each factor and growth period indicate significant differences at $p < 0.05$ (*) or $p < 0.01$ (**); ns = no significant difference.

Yield, yield components and rice grain quality

The yield and yield component parameters (panicle length, number of grains per panicle, number of filled grains, 1,000-grain weight and straw yield) were highly affected by both the water management and the variety, but not influenced by the combination effect of both factors (Table 3). The rice plants grown under AWD25 consistently exhibited significantly ($p < 0.01$) greater values for panicle length, number of grains per panicle, number of filled grains, 1,000-grain weight and straw yield than CF. In the variety comparison, Leenok rice consistently had significantly ($p < 0.01$) higher values of the above parameters than RD22 rice. However, the combination effect of both factors (water level and variety) on the above values was not significant.

In contrast, the combination effect of the water management and the variety on the panicle number per hill, yield and harvesting index was significant ($p < 0.01$), as shown in Table 3. The number of panicles per hill of Leenok rice plants grown under AWD25 was significantly ($p < 0.01$) higher than those grown under CF and greater than RD22 rice grown under both conditions, while the numbers of panicles per hill for the RD22 rice grown under both CF and AWD25 were not significantly different. In addition, the yield of Leenok rice grown under AWD25 was the highest, followed by Leenok rice grown under CF, whereas the yields of RD22 rice grown under both CF and AWD25 were the lowest. Furthermore, the harvesting index of the RD22 rice grown under AWD25 was significantly ($p < 0.05$) lower than for the other treatments.

Table 3 Yield and yield components of glutinous rice as affected by different water management regimes under field conditions

Factor	Number of panicles/hill	Panicle length (cm)	Number of grains/panicle	Filled grains (%)	1,000-grain weight (g)	Yield (kg/ha)	Straw yield (kg/ha)	Harvest index
A (Water management)								
CF	18.86 ± 0.64^{b}	26.41 ± 0.39^{b}	166.25 ± 2.56^{b}	78.16 ±0.48^{b}	21.09 ± 0.04^{b}	3,000 ± 13.91^{b}	3,418 ± 33.59^{b}	0.52 ± 1.34^{b}
AWD25	21.98 ± 1.44^{a}	27.78 ± 0.90^{a}	173.88 ± 5.79^{a}	80.78 ± 1.10^{a}	21.22 ± 0.11^{a}	3,131 ± 31.45^{a}	3,956 ± 76.00^{a}	0.55 ± 3.03^{a}
F test	**	**	**	**	**	**	**	*
B (Variety)								
Leenok	21.84 ± 0.64^{a}	29.11 ± 0.39^{a}	179.50 ± 2.56^{a}	80.49 ± 0.48^{a}	21.87 ± 0.04^{a}	3,256 ± 13.91^{a}	4,156 ± 33.59^{a}	0.56 ± 1.34^{a}
RD22	19.01 ± 1.44^{b}	25.08 ± 0.90^{b}	160.63 ± 5.79^{b}	78.45 ± 1.10^{b}	20.44 ± 0.11^{b}	2,875 ± 31.45^{b}	3,218 ±76.00^{b}	0.52 ± 3.03^{b}
F test	**	**	**	**	**	**	**	*
A × B (Combination)								
Leenok × CF	19.14 ± 0.90^{b}	28.58 ± 0.56	174.50 ± 3.62	78.91 ± 0.69	21.81 ± 0.06	3,068 ± 19.66^{b}	3,956 ± 47.51	0.56 ± 1.89^{a}
Leenok × AWD 25	24.53 ± 2.04^{a}	29.64 ± 1.27	184.50 ± 8.20	82.07 ± 1.56	21.94 ± 0.15	3,444 ± 44.48^{a}	4,356 ± 107.49	0.55 ± 4.29^{a}
RD22 × CF	18.58 ± 0.90^{b}	24.24 ± 0.56	158.00 ± 3.62	77.40 ± 0.69	20.38 ± 0.06	2,925 ± 19.66^{c}	2,882 ± 47.51	0.49 ± 1.89^{b}
RD22 × AWD25	19.43 ± 2.04^{b}	25.91 ± 1.27	163.25 ± 8.20	79.50 ± 1.56	20.50 ± 0.15	2,818 ± 44.48^{c}	3,600 ± 107.49	0.55 ± 4.29^{a}
F test	**	ns	ns	ns	ns	**	ns	*
CV (%)	6.27	2.95	3.01	1.23	0.46	2.84	8.49	4.95

CF = continuous flooding; AWD25 = moderate water stress; CV = coefficient of variation.
Means (±SD) within each column with different lowercase superscript letters for each factor and growth period indicate significant differences at $p < 0.05$ (*) or $p < 0.01$ (**); ns = no significant difference.

Table 4 Correlation analysis of yield and yield components data of glutinous rice as affected by different water management regimes under field conditions

Water management factor ($n = 16$)	Number of panicles	Panicle length	Total grains	Filled grains	Grain weight	Straw yield	Harvest index
Panicle length	0.54*						
Total grains	0.66**	0.88**					
Filled grains	0.63**	0.74**	0.73**				
Grain weight	0.55*	0.92**	0.89**	0.57**			
Straw yield	0.65**	0.88**	0.78**	0.76**	0.80**		
Harvest index	0.31	0.66**	0.47	0.59**	0.50*	0.85**	
Yield	0.80**	0.72**	0.81**	0.62**	0.80**	0.65**	0.19

Variety factor ($n = 16$)	Number of panicles	Panicle length	Total grains	Filled grains	Grain weight	Straw yield	Harvest index
Panicle length	0.57						
Total grains	0.80**	0.66					
Filled grains	0.77*	0.68*	0.88**				
Grain weight	0.61	0.48	0.72*	0.61			
Straw yield	0.62	0.72*	0.50	0.54	0.30		
Harvest index	-0.02	0.28	0.09	-0.03	-0.40	0.68	
Yield	0.84**	0.60	0.77*	0.75*	0.88**	0.48	-0.30

*, ** = significant at $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference.

Pearson's correlation analysis of the data showed that all parameters of the yield and yield components were positively correlated under the different water management regimes (Table 5). Based on the water management factor, the yields of both glutinous rice varieties were positively correlated ($p < 0.01$) with panicle number, panicle length, total grains, filled grains, 1,000-grain weight and straw yield, but not with HI. For the variety factor, yield was positively well correlated with panicle number, total grains, filled grains and 1,000-grain weight. The quality of the rice grain as affected by the water management and the variety is shown in Fig. 1, with the percentages of full grains and broken grains also being influenced by the water level and the variety. The full grain percentage was better under CF than AWD25 (Fig. 1A) and the Leenok variety had a higher full grain percentage than the RD22 variety (Fig. 1B). In contrast, the number of broken grains under CF was significant ($p < 0.01$) lower than that of AWD25 (Fig. 1C) and Leenok had significant ($p < 0.01$) lower broken grain than RD22 variety (Fig. 1D). However, there was no combination effect of both factors (water level and rice variety) on all grain quality parameters.

Rice plant physiological responses

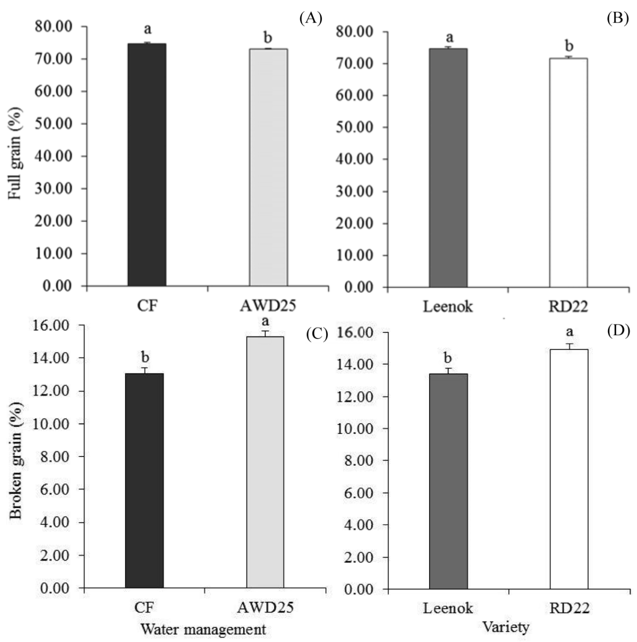
The RGR of the glutinous rice plants was highly affected by the water management regimes, but not by the variety or the combination of both factors during the first 45 DAT (Table 5). During the first 30 DAT, the rice plants grown under CF had a significantly ($p < 0.01$) lower RGR than those grown under AWD25, whereas it was the opposite during 30–45 DAT, with the RGR of the rice plants under CF being significantly ($p < 0.01$) greater than for AWD25. At 45–60 DAT, the combination effect of both factors was significant ($p < 0.01$), with the Leenok variety grown under CF having the highest RGR, followed by Leenok rice under AWD25, while the RGR of RD22 rice was not significantly different under both conditions.

The SLW of the rice leaves was also highly affected by the water management ($p < 0.01$), as shown in Table 6. The rice plants grown under AWD25 had significantly ($p < 0.01$) higher values of SLW than those grown under CF at 30 DAT. At 45 DAT and 60 DAT, there was a significantly ($p < 0.01$) combination effect of the factors on SLW, with the Leenok variety grown under AWD25 having the highest SLW value, followed by RD22 grown under AWD25 and CF conditions, whereas the Leenok rice grown under CF had the lowest SLW values.

Table 5 Relative growth rate (RGR) of rice leaves of both glutinous rice varieties under different water management regimes during 30–60 d after transplanting

Factor	RGR (mg/g/d)		
	0–30 d	31–45 d	45–60 d
A (Water management)			
CF	54.62 ± 1.00[b]	33.00 ± 1.28[a]	26.00 ± 0.51[b]
AWD25	60.37 ± 2.06[a]	27.00 ± 2.89[b]	28.00 ± 1.15[a]
F test	**	**	**
B (Variety)			
Leenok	57.25 ± 1.00	29.37 ± 1.28	29.00 ± 1.15[a]
RD22	57.75 ± 2.06	30.62 ± 2.89	25.00 ± 0.51[b]
F test	ns	ns	**
A × B (Combination)			
Leenok × CF	53.75 ± 1.41	31.50 ± 1.81	32.00 ± 0.72[a]
Leenok × AWD25	60.75 ± 3.19	27.25 ± 4.09	26.00 ± 1.62[b]
RD22 × CF	55.50 ± 1.41	34.50 ± 1.81	24.00 ± 0.72[b]
RD22 × AWD25	60.00 ± 3.19	26.75 ± 4.09	26.00 ± 1.62[b]
F test	ns	ns	**
CV (%)	3.12	13.38	4.70

CF = continuous flooding; AWD25 = moderate water stress; CV = coefficient of variation.
Means (±SD) within each column with different lowercase superscript letters for each factor and growth period indicate significant differences at $p < 0.01$ (**); ns = no significant difference.



Factor	Full grain	Broken grain
F test A	**	**
B	**	**
A × B	ns	ns
CV (%)	0.79	5.01

Fig. 1 Number of full grains and broken grains of rice plants for different factors: (A) and (C) water management; (B) and (D) variety, respectively, where different lowercase letters above bars indicate significant differences at $p < 0.01$ (**), ns = no significant difference; error bars indicate ± SD; CV = coefficient of variation.

Table 6 Specific leaf weight (SLW) and leaf area index (LAI) of rice leaves of both glutinous rice varieties under different water management regimes at 30 d, 45 d and 60 d after transplanting

Factor	SLW (mg/cm^2)			LAI (mg/cm^2)		
	30 d	45 d	60 d	30 d	45 d	60 d
A (Water management)						
CF	147 ± 11.93^b	179 ± 12.49^b	172 ± 9.35^b	0.31 ± 0.01^b	0.84 ± 0.03^b	2.22 ± 0.08^b
AWD25	229 ± 27.00^a	346 ± 28.47^a	417 ± 21.16^a	0.55 ± 0.04^a	1.37 ± 0.08^a	4.08 ± 0.19^a
F test	**	**	**	**	**	**
B (Variety)						
Leenok	176 ± 11.93	269 ± 12.48	335 ± 9.35^a	0.39 ± 0.01^b	1.00 ± 0.03^b	2.98 ± 0.08^b
RD22	200 ± 27.00	256 ± 28.47	254 ± 21.16^b	0.46 ± 0.04^a	1.20 ± 0.08^a	3.31 ± 0.19^a
F test	ns	ns	**	**	**	**
A × B (Combination)						
Leenok × CF	133 ± 16.88	158 ± 17.67^d	148 ± 13.23^d	0.28 ± 0.02	0.64 ± 0.05^c	1.40 ± 0.12^c
Leenok × AWD25	219 ± 38.19	380 ± 39.98^a	523 ± 29.93^a	0.51 ± 0.06	1.37 ± 0.12^a	4.57 ± 0.28^a
RD22 × CF	162 ± 16.88	199 ± 17.67^c	196 ± 13.23^c	0.33 ± 0.02	1.05 ± 0.05^b	3.03 ± 0.12^c
RD22 × AWD25	239 ± 38.19	313 ± 39.98^b	312 ± 29.93^b	0.59 ± 0.06	1.36 ± 0.12^a	3.59 ± 0.28^b
F test	ns	**	**	ns	**	**
Coefficient of variation (%)	12.69	9.53	6.35	9.01	6.84	5.58

SLW = specific leaf weight; LAI = leaf area index; CF = continuous flooding; AWD25 = moderate water stress; CV = coefficient of variation.
Means (±SD) within each column with different lowercase superscript for each factor and growth period indicate significant differences at $p < 0.01$ (**); ns = no significant difference.

In addition, the LAI of the rice plants was greatly influenced by both the water management and the variety ($p < 0.01$), as shown in Table 6. The LAI values of the rice plants grown under AWD25 were significantly ($p < 0.01$) greater than those under CF, with the Leenok variety having greater values of LAI than RD22 at 30 DAT. The combination effect of the factors had a significantly ($p < 0.01$) effect on the LAI at 45 DAT and 60 DAT, with the LAI values of the rice plants of both varieties grown under AWD25 being significantly ($p < 0.01$) higher than those under CF at 45 DAT, whereas at 60 DAT, the Leenok variety under AWD25 had the highest LAI value, followed by RD22 rice grown under AWD25, with the Leenok and RD22 rice plants grown under CF having the lowest LAI values.

The influence of different water management regimes on the leaf pigment contents of both glutinous rice varieties are shown in Table 7. The Chl a of the rice plants grown under CF condition was significantly ($p < 0.01$) higher than those under AWD25; however, there was no significant difference between the Leenok and RD22 varieties and no combination effect was evident for leaf Chl a. In contrast, there were no significant effects of water management and the variety as well as the combination effect of both factors on the Chl b content. For Chl a + Chl b, the leaves of the rice plants grown under CF had significantly ($p < 0.01$) higher Chl a + Chl b than those under AWD25, with the RD22 variety containing significantly ($p < 0.01$) greater Chl a + Chl b than the Leenok variety. However, there was no significant combination effect on Chl a + Chl b. In addition, the Chl a / Chl b was greatly affected by the water management, with the rice plants grown under CF having significantly ($p < 0.01$) higher values than those under AWD25; however, there was no significant effect of variety or of the combination of both factors on Chl a / Chl b. In contrast, the leaf carotenoid content of the rice plants grown under AWD25 was significantly ($p < 0.01$) higher than those grown under CF, though the effects of the variety and the combination of both factors on carotenoids were not significant.

Leaf total non-structural carbohydrates and grain starch and sucrose

Water management significantly ($p<0.01$) affected the accumulation of leaf TNC and grain sucrose and starch (Table 8). The rice plants grown under CF had significantly ($p<0.01$) greater leaf TNC than those under AWD25, while there was no significant difference in leaf TNC between the Leenok and RD22 varieties and no combination effect of both factors on leaf TNC. There were significantly ($p < 0.01$) effects of water management on grain sucrose and starch accumulation. The rice plants grown under CF had a greater accumulation of sucrose in the grain than those grown under AWD25, whereas it the opposite was observed for starch accumulation, with those grown under AWD25 having a significantly ($p < 0.01$) higher content of grain starch than those under CF. In the variety comparison, the Leenok rice accumulated significantly ($p < 0.01$) higher contents of both grain sucrose and starch than the RD22 rice. However, there was no combination effect of both factors (water management and rice variety) on the grain sucrose and starch contents.

Table 7 Leaf pigment contents, carotenoids and leaf total non-structural carbohydrate content (TNC) at 60 d after transplanting for different water management regimes

Factor	Chlorophylls and carotenoids (mg/g FW)				
	Chl a (mg/g FW)	Chl b (mg/g FW)	Chl a + Chl b (mg/g FW)	Chl a / Chl b (mg/g FW)	Carotenoids (mg/g FW)
A (Water management)					
CF	2.06 ± 0.11[a]	0.83 ± 0.08	2.89 ± 0.09[a]	2.63 ± 0.34[a]	0.55 ± 0.06[b]
AWD25	0.80 ± 0.25[b]	0.74 ± 0.18	1.55 ± 0.22[b]	1.41 ± 0.79[b]	0.83 ± 0.15[a]
F test	**	ns	**	**	**
B (Variety)					
Leenok	1.32 ± 0.11	0.73 ± 0.08	2.05 ± 0.09[b]	2.10 ± 0.34	0.67 ± 0.06
RD22	1.54 ± 0.25	0.84 ± 0.18	2.39 ± 0.22[a]	1.93 ± 0.79	0.71 ± 0.15
F test	ns	ns	**	ns	ns
A × B (Combination)					
Leenok×CF	1.83 ± 0.16[b]	0.80 ± 0.11	2.63 ± 0.14[a]	2.37 ± 0.49[a]	0.52 ± 0.09[b]
Leenok×AWD25	0.80 ± 0.36[c]	0.66 ± 0.26	1.46 ± 0.31[b]	1.82 ± 1.11[b]	0.82 ± 0.21[a]
RD22×CF	2.28 ± 0.16[a]	0.86 ± 0.11	3.15 ± 0.14[a]	2.87 ± 0.49[a]	0.58 ± 0.09[b]
RD22×AWD25	0.80 ± 0.36[c]	0.82 ± 0.26	1.63 ± 0.31[b]	0.98 ± 1.11[b]	0.84 ± 0.21[a]
F-test	**	ns	**	**	**
CV (%)	15.94	20.69	8.95	34.67	19.79

Chl a = chlorophyll a; Chl b = chlorophyll b; Chl a + Chl b = total chlorophyll; Chl a / Chl b = ratio of chlorophyll a / chlorophyll b; FW = fresh weight; CV = coefficient of variation.

Means (±SD) within each column with different lowercase superscript letters indicate significant differences for each factor and growth period at $p < 0.01$ (**); ns = no significant difference.

Table 8 Leaf total non-structural carbohydrate content (TNC), grain sucrose at 100 d after transplanting under different water management regimes

Factor	TNC (mg/g DW)	Sucrose (mg/g DW)	Starch (mg/g DW)
A (Water management)			
CF	0.31 ± 0.01[a]	1.59 ± 0.04[a]	34.90 ± 1.4[b]
AWD25	0.25 ± 0.03[b]	0.42 ± 0.03[b]	41.89 ± 1.5[a]
F test	**	**	**
B (Variety)			
Leenok	0.28 ± 0.01	1.05 ± 0.05[a]	40.29 ± 1.9[a]
RD22	0.28 ± 0.03	0.96 ± 0.04[b]	36.52 ± 1.7[b]
F test	ns	*	*
A × B	ns	ns	ns
CV (%)	10.41	7.98	7.31

DW = dry weight; CV = coefficient of variation.

Means (±SD) within each column with different lowercase superscript letters for each factor and growth period indicate significant differences at $p < 0.05$ (*) and $p < 0.01$ (**); ns = no significant difference.

Correlation analysis was undertaken to evaluate the source-sink relationship between the rice leaves and the grains, as well as yield (Table 9). Based on the results, under both factors (water management and rice varieties), the yield was positively correlated with the grain starch content, whereas the grain sucrose content had negative and positive correlations ($p < 0.01$) with the grain starch content and the leaf TNC, respectively.

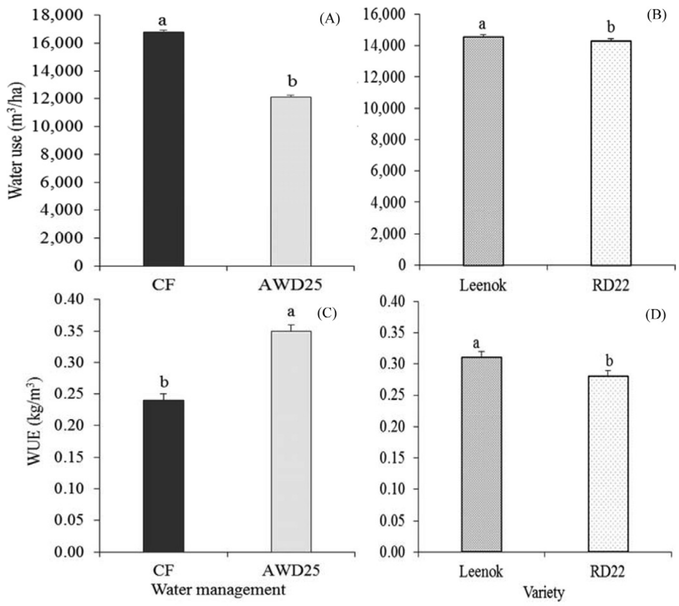
Table 9 Correlations among yield, grain sucrose, grain starch and leaf total non-structural carbohydrate content (TNC) under different water management regimes

	Water management factor (n = 16)		
	Yield	Grain sucrose	Grain starch
Grain sucrose	-0.31		
Grain starch	0.48*	-0.71**	
TNC	-0.33	0.75**	-0.43
	Variety factor (n = 16)		
	Yield	Grain sucrose	Grain starch
Grain sucrose	-0.35		
Grain starch	0.55*	-0.73**	
TNC	-0.35	0.78**	-0.45

*, ** = significant at $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference.

Water use and water use efficiency

Both the water use and WUE of the glutinous rice plants were significantly ($p < 0.01$) affected by the water management regimes. The CF treatment consumed a significantly ($p < 0.01$) greater amount of water than AWD25 (Fig. 2A), resulting in a significantly ($p < 0.01$) lower WUE value compared to AWD25 (Fig. 2C). Furthermore, the Leenok variety had a higher water use (Fig. 2B) but a better WUE (Fig. 2D) than RD22. There was a significant ($p < 0.01$) effect for the combination of both factors (water level and variety) for WUE, with both varieties having similarly lower WUE values under CF, whereas Leenok had a greater WUE than RD22 under AWD25.



Factor	Water use	WUE
F test A	**	**
B	*	**
A × B	ns	**
CV (%)	2.78	3.81

Fig. 2 Water use and water use efficiency (WUE) of rice plants for different factors: (A) and (C) water management; (B) and (D) variety, respectively, where different lowercase letters above bars indicate significant differences at $p < 0.05$ (*) or $p < 0.01$ (**), ns = no significant difference; error bars indicate ± SD; CV = coefficient of variation.

Discussion

The overall results of this study indicated both glutinous rice varieties (Leenok and RD22) seemed to perform better in many aspects under moderate water stress (AWD25) compared to CF, with the Leenok local variety outperforming the RD22 modern variety in many aspects. Although the plant height was not affected by the water management, there was a slightly different growth pattern observed in the early growth stage (15–60 DAT) with the RD22 rice seemingly growing more rapidly than the Leenok variety, although there was no difference at 100 DAT, indicating that both varieties were able to adapt and resumed normal growth under both water management regimes. In contrast, the combination effect of both factors (water management and rice variety) on the tiller number per hill of the rice plants was highly significant ($p < 0.01$), with the tiller number of Leenok rice under AWD25 being consistently greater than for the RD22 rice and other treatments, suggesting that a local, native variety (Leenok) performed better than a modern, improved variety (RD22) under moderate water stress management (AWD25). Some yield and yield component parameters, such as panicle length, number of grains per panicle, number of filled grains, 1,000-grain weight and straw yield, were significantly ($p < 0.01$) greater under moderate water stress (AWD25) than under CF, with the Leenok rice having consistently greater values for these parameters than the RD22 rice. In addition, yield and yield components, such as number of panicles per hill, grain yield and HI were greatly influenced by the combination effect between the water management and the rice variety—Leenok rice grown under AWD25 had the highest panicle number per hill and grain yield compared to the other treatments, while RD22 rice grown under AWD25 had the lowest HI. These results suggested that there was a significant effect of the water management on the productivity of the glutinous rice plants and that the different varieties of the glutinous rice responded differently under different water management regimes. The difference in the rice response was likely due to the difference in tillering capacity of the rice plants under AWD25, as previously discussed; furthermore, all components of the yield were closely correlated.

The overall results suggested that the glutinous rice plants did not need a continuous water supply providing a high level of water all the time to maintain growth and the ability to increase tillering capacity, as well as yield. Therefore, appropriate intermittent water supply management under a suitable AWD regime to produce moderate water stress would be suitable to sustain growth as well as yield under the field conditions associated with the relatively poor soil fertility conditions in northeast Thailand. In fact, Maneepitaka et al. (2019) reported that an AWD regime increased grain yield by 7–15% compared to a CF regime and yield components, such as panicle number and 1,000-grain weight were also higher under AWD than under CF. However, severe AWD (when the soil dried beyond -20 kPa) could result in yield losses of 22.6% relative to CF (Carrijo et al., 2017). The greater number of productive tillers of the rice plants grown under AWD might be related to the accumulation of plant leaf phytohormones, such as abscisic acid (ABA) and cytokinins as the precursor of the biosynthesis of both hormones, as isopentenyladenine increased by 37% under AWD compared to CF, which might lead to an increased grain mass compared to the plants grown under CF (Norton et al., 2017). Notably, grain quality (sucrose accumulation, numbers of full grains and broken grains) of the glutinous rice under AWD25 was lower than under CF, resulting in a slightly negative impact of such water management.

This was the opposite to Zhao et al. (2021), who reported that intermittent flooding (alternate wetting and drying) generally improved the grain quality. However, more thorough study is required on several aspects of grain quality, including cooking and eating quality and aromatic profiling related to volatile compound production, to quantify the eating and cooking quality of the rice grain, as Prodhan and Shu (2020) reported that the 2-AP content (the main aromatic compound in the rice grain) may increase under stress conditions, such as in drought-sensitive regions or areas with arid, sandy soil. In addition, the rice aromatic properties could be influenced by many environmental factors such as temperature, relative humidity, moisture content, pH, day length, sunlight intensity and soil type (Kaewmungkun et al., 2023).

The leaf pigment contents (Chl a, Chl a+b and Chl a/b) were greater under CF than under AWD25; however, this did not affect the growth of the rice plants as there was no significant difference in plant height between CF and WAD25. In addition, greater RGR, SLW and LAI values under AWD25 than under CF were evident throughout the growth period; furthermore, tillering capacity of the rice plants under AWD25 was better than under CF. These results suggested that a moderate water deficit (AWD25) could sustain the growth of both glutinous rice varieties under field conditions. Furthermore, Leenok had better RGR and SLW values, but lower LAI values than RD22, suggesting that the local variety outperformed the modern variety under the studied experimental conditions. The higher carotenoid contents under AWD25 than under CF indicated that the rice plants had the ability to cope with moderate water deficit conditions, as carotenoids play an important role in protection of the photosynthetic apparatus to allow photosynthesis to function normally, as shown in another report (Phomvongsa et al., 2024, personal communication). The glutinous rice plants might also exhibit other mechanisms to respond to abiotic stresses, such as drought and cold stress, at the physiological, biochemical and the molecular levels, as recently reported by Kim et al. (2024) with plants altering the biosynthesis, catabolism and transport of ABA, which plays a major role in responses to drought stress by coordinating responses at the cellular and the physiological levels to cope with the adverse conditions. In addition, ABA affects the expression of several genes that enable rice plants to survive stress by inducing stomatal closure by the guard cells, with water stress resulting in the accumulation of ABA levels as high as 300–1,500 mg/g FW (Zhu et al., 2017, 2020). In addition, the amount of leaf TNC, which signifies the total amount of sucrose and free sucrose and fructose in the leaves, and the accumulation of both grain sucrose and starch showed positive and negative correlations (Table 8), suggesting that under the influence of both factors (water management and rice variety), the leaf TNC was positively correlated to the grain sucrose, while the grain starch was negatively correlated to the grain sucrose. These outcomes provide some indirect evidence of the sink and source relationship between the rice organs where some alteration and adjustment of the phloem loading and unloading activity between the source (leaves) and the sink organ (grain) occurred during grain filling, as well as conversion between sucrose and starch and *vice versa* (Wei et al., 2018). The grain starch of the rice plants grown under AWD25 was notably higher than under CF and the Leenok rice had a higher level of grain starch than the RD22 rice (Table 8). In addition, there was a positive correlation between the starch content and the rice yield (Table 9) for the Leenok rice under AWD25, which produced the greatest yield of all treatments (Table 3). These results implied that the greater rice yield under AWD25 was highly related to the higher accumulation of grain starch.

The magnitude of the water consumption reduction for the glutinous rice production under the intermittent water management cycle under field conditions in sandy loam soils of northeast Thailand showed that a moderate water stress regime (AWD25) used 27.83% less water and had a 31.43% better WUE than CF. This could be considered as one of the most important findings of the current study, which is in line with other studies. For example, Maneepitaka et al. (2019) showed that AWD reduced total water input by 19% and 39%, resulting in improved water productivity by 46% and 77% in the wet and dry seasons, respectively, compared to CF. The impact analysis of safe AWD practice showed a reduction in the hours of irrigation use by about 38% without a significant reduction in yields and profits (Rejesus et al., 2011). In addition, the results from the current study confirmed that under a moderate water stress (AWD25), both varieties (Leenok and RD22) of the glutinous rice plants were able to adjust and produce underlining physiological responses in order to grow and adapt to the intermittent water management under field conditions in northeast Thailand with well-drained soil for dryland rice cultivation, without affecting growth and yield. In addition, unlike many other studies that have reported hybrid rice varieties tending to perform better than native or local varieties under AWD practice in general, the current study confirmed that for glutinous rice, a local variety (Leenok) outperformed the improved, hybrid variety (RD22) in many aspects under the AWD25 regime. Notably, Thailand, as one of the leading the world's rice producers and exporters, needs to explore and expand knowledge on the application of AWD practice to adapt this technology for sustainable rice production under the current climate change situations. However, based on the literature review there have been only a very limited number of systemic studies on the impact of alternate wetting and drying practices on rice production, especially for off-season production of glutinous rice. As a result, the findings in the current have provided one of the first studies on glutinous rice. However, further study should explored the responses of different rice varieties under AWD practices, since other reports have shown that different varieties under different growing conditions responded differently under such water control practices.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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