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Water Productivity and Harvest Index Response of Paddy Rice with Alternate Wetting and Drying Practice for Adaptation to Climate Change

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Abstract: The current water scarcity and world population increase cause the need for more food, pushing the demand on water resources due to crop production such as rice. Increasing agricultural water productivity by reducing the amount of irrigation water without affecting the yields, especially in paddy rice, is necessary. This is possible with alternate wetting and drying (AWD) irrigation. This study was conducted under greenhouse conditions at Tokyo University of Agriculture and Technology, Japan to evaluate the response of yield, water productivity and harvest index with different water regimes. The experiment was performed in pots with four water regimes as treatments and three replications, making 12 pots. The water regimes were continuous flooding irrigation as control and three AWD conditions—AWD5, AWD10 and AWD15—in which pots were irrigated when water reached 5, 10 and 15 cm soil depth, respectively, after the disappearance of surface ponding water. Yield components, harvest indexes and water productivity showed no significant difference ($p < 0.05$) between irrigation treatments. In this research, as there is more than a 25% reduction in water use and only 6.4% in grain yield, AWD15 was considered the best irrigation practice among the other treatments. This study provides data reference for theoretical scientific knowledge and understanding of safe AWD practice for countries facing water shortages.

Keywords: drought; irrigation water management; ponding water; soil drying

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1. Introduction

Water scarcity is becoming a bigger global concern. Additionally, irrigation agriculture uses over 70% of the world's fresh water, and the demand is expected to increase to meet future food security. Drought is becoming a serious global issue and crises in many countries contributing to water scarcity, the drying of water sources such as lakes, rivers and seasonal streams and reducing irrigated rice yields [1]. Rice is one of the most staple food crops; it is critically important for food security to half of the world's population, where rice accounts for about 80% of their food consumption [2,3]. In addition, 114 countries grow rice, and more than 50 have an annual production of 100,000 tons of rice or more [4]. Rice has been cultivated in more than 146.5 million hectares of the world agricultural lands [5,6], although the production is significantly affected by drought issues. As in most sub-Saharan African countries, rice is one of the cereal crops grown in Uganda mostly by smallholder farmers for income [7] with few large schemes and total production of 350,000 MT annually (upland and paddy).

For a long time, paddy rice cultivation has been carried out using the traditional continuous flooding (CF) irrigation which provides enough water supply and weed management by keeping root zones in anaerobic conditions. The anaerobic conditions in paddy rice fields result from oxygen restrictions in the soil due to the long duration of ponded water in the field after flooding. The same conditions were observed with pot experiments in CF mostly at the vegetative to reproductive stages. Traditional CF is being practiced by smallholder farmers in Uganda who face several challenges such as underdeveloped irrigation and water structures, poor water management and drying of water sources due to drought [8]. In contrast, the country's rainfall pattern can support two rice seasons in the year, with precipitation of 750 mm/year in the driest areas in the northeast to 1500 mm/year in the high rainfall areas of the northern, eastern, and western parts of the country [9]. This is becoming impossible due to climate change, since rice cultivation under the traditional system demands higher water input than the other cereal crops [10].

On the other hand, the water demand is increasing for both domestic and industrial use. This contributes to a reduction in the water availability for agriculture purposes and water conflicts among water users and among farmers which cannot be avoided. Additionally, surface and underground water resources are shrinking, which is posing a threat to the future of rice production [11]. The current challenge for paddy rice cultivators is to increase the water productivity by growing rice with less water, which is possible [12,13]. The promotion and adoption of effective water use-saving techniques for rice production to reduce water use in the agricultural sector without affecting the yields [14], with climate change being inevitable, is necessary. Alternate wetting and drying (AWD) irrigation is one of the water-saving techniques widely being promoted for rice cultivation [15]. It has been considered as a climate-smart water-saving technique being practiced in many Asian countries such as China, Bangladesh, India, and Vietnam [16–18].

The AWD practice was developed by the International Rice Research Institute (IRRI) in the 1970s [19,20]. The practice comprises three basic elements: (1) shallow flooding for the first 2 or 3 weeks after seeding or transplanting to recover seedlings from transplanting shock and to suppress weed emergence [21], (2) ponding layer of 2–5 cm of standing water from panicle initiation (PI) to the end of flowering because this duration is very sensitive to any water stress, and (3) AWD cycle through the rest of the crop growth periods [22]. The AWD system ensures supply of the physiological water demand [23] of rice by controlling water supply and reducing the total water input. In AWD, fields are subjected to periodic cycles of wetting and drying of soil, which is closely linked with the number of factors such as the soil texture, soil water potential, plant water status, and soil hydraulic conductivity [24]. The field water observation tube developed by IRRI can be used to monitor the water level beneath the soil surface. Half-perforated field water tubes can be made using bamboo, PVC pipe, tin cans, or even plastic bottles with a diameter of 10–20 cm and based on the materials availability. Using perforated field water tubes enables farmers to monitor the water table easily. Water is first applied to a depth of around 5 cm, and then, the farmers wait until the perched water table falls to a certain limit beneath the soil surface due to percolation, drainage, and evapotranspiration. The fields are then re-irrigated when the field water level (FWL) reaches 15 cm or less (in water pipes) below the soil surface, which is referred to as ''safe AWD" [25]. The threshold level at "safe AWD" increases or maintains the yield with water saving of 15–30%, as at this threshold level, the roots of plants are still able to acquire sufficient water from the saturated soil and perched groundwater for growth and development [23]. Farmers are encouraged to implement the "safe AWD" technique during vegetative growth (tillering to PI) and then at the grain-filling stage [26].

Several studies have reported that compared to traditional continuously flooding conditions, AWD can maintain or even increase grain yield [16–18]. In contrast, a yield penalty is commonly observed under AWD compared with traditional continuous flooding [19,20]. Generally, AWD increased water productivity with respect to total water input because the yield reduction was smaller compared to the amount of water saved [17].

AWD can save water while maintaining rice yields, but in some countries, its adoption by farmers remains limited due to lack of knowledge and skills, perception due to the key knowledge gaps in AWD practice which include its effect on early vegetative vigor, unknown relationship with yield and water use efficiency based on different local cultivars used by smallholder farmers, and the socio-economic factors influencing AWD irrigation scheduling, which involves frequent field monitoring [27]. Additionally, there are two primary methods to further increase rice yield. The first is to increase the harvest index (HI) when the biological yield is certain [28]. The second is to increase the biological yield under the condition of a certain HI. The HI is the ratio of the crop marketable yield to the biological yield. This concept was first proposed by the former Soviet scholar Niki Porovich in 1954 [29]. Currently, a series of studies have been conducted to increase yields by improving HI [30]. The research by Mai et al. [31] showed that the cultivation method of sowing effectively improved the rice HI. It is important to note that one aspect of field research such as experimental studies with crop cultivation should be carried out for at least two or more seasons [32].

One of the challenges is defining the AWD practice. Since the water application is based on either soil water potential or field water level, there are three categories of AWD conditions: safe-AWD, mild/moderate-AWD, and severe-AWD approach. Safe AWD is defined by field water level when the water level reaches less or 15 cm depth below the soil surface [23], while mild AWD condition is when the water level reaches 15 to 20 cm and severe AWD is when the FWL reaches 25 cm. Safe AWD is considered appropriate, since it has a minimal effect on yield. Additionally, the AWD practice by matric potential is defined when the matric potential head in the rootzone reaches −20 kPa or less for safe AWD, −45 kPa for mild AWD or −70 kPa for severe AWD [14]. This relationship varies depending on the soil type, soil hydraulic conductivity, environmental factors and farmers' experience. Whereas IRRI recommends water application with AWD practice two or three weeks after transplanting or direct seeding [19,20], then there is continuous flooding at the panicle initiation to the end of flowering, since this stage of rice is sensitive to any water stress [22]. However, in this research, water regimes in AWD conditions were set under safe AWD (less or 15 cm depth), and the water regime was defined when FWL reached 5, 10 and 15 cm depth below the soil surface to evaluate safe AWD. The water application after the start of the water regimes was carried out throughout the whole cultivation period, which is opposed to the IRRI recommendations. The effect of water regimes with safe AWD practice throughout the whole cultivation period has not been studied. Similarly, if promoted, for example, in Uganda, the safe AWD practice can enhance water use and management since the government, through agricultural and rice sector development and investment plans, is rehabilitating irrigation schemes to increase paddy cultivation [8].

In this study, the response of water productivity and HI was studied by analyzing the rice yield data, seasonal water use, dry matter accumulation, and HI under different safe AWD regimes throughout the whole season. Therefore, the objectives of this research are (1) to apply and evaluate the FWL of safe AWD practice to determine the appropriate observation depth leading to optimum water use, and (2) to evaluate water productivity, water saving, and HI under the different safe AWD regimes. The findings of the present study provide useful information to farmers carrying out paddy rice cultivation in countries facing water shortages due to climate change and drought. The study also provides scientific knowledge on the application of safe AWD practice throughout the whole season.

2. Materials and Methods

2.1. Experimental Design and Site Characteristics

The study was carried out from December 2021 to March 2022 in glass greenhouses at Tokyo University of Agriculture and Technology (TUAT), Fuchu, which has a longitude and latitude of 139.4787° E, 35.6840° N, respectively, and is 67 m above sea level. The temperature inside the glass greenhouse was set between 20 and 30°C. Paddy soils were collected from the Honmachi experimental field of TUAT and sieved with a 4 mm sieve. The site has clay loam soils as defined by the United States Department of Agriculture (USDA) of soil texture classification. Meteorological data such as temperature, relative humidity, and solar radiation were measured and recorded from a meteorological station placed within the glass greenhouse. Additionally, relative humidity and temperature sensors were placed in all the glass greenhouses. The average relative humidity and temperature during the cultivation experiment are plotted in the Figure 1.

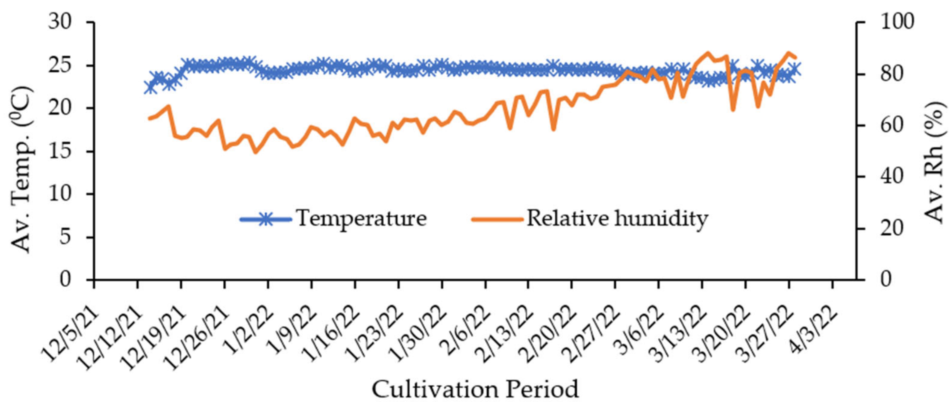

Figure 1. Average temperature and relative humidity conditions in glass greenhouses, where Av. Tempe.; average temperature and Av. Rh (%); average relative humidity.

Water Regimes

The pots in the glass greenhouses were arranged in a randomized block design with four treatments and three replications as described below:

The continuous flooding irrigation (CF) as a control treatment was applied during the whole rice-growing period, in which water was applied when ponded water dropped to a zero level on the soil surface. The water application to the pots was always measured and applied by a watering can.

Alternate wetting and drying (AWD) conditions described as AWD5, AWD10 and AWD15 correspond to the irrigation period when water level in the observation tube reaches 5, 10 and 15 cm in soil depth after the disappearance of surface ponding water, respectively. All the AWD conditions fall under the safe approach recommended by the International Rice Research Institute (IRRI) not to cause yield decline [33]. However, in this research, water was applied through the whole cultivation period in AWD regimes after the start of irrigation treatments, which is opposed to the IRRI recommendations. The AWD wetting and drying conditions are shown in the schematic illustration in Figure 2.

All pots were of the same size of 24 cm diameter and 30 cm height with a closed bottom. In total, 12 experimental pots were placed in two glass greenhouses of the same conditions, as shown in Figure 3. Paddy soils collected from the experimental paddy field of TUAT were packed in the pots with the same dry density of the field soil to maintain the field conditions after sieved with a 4-mm sieve.

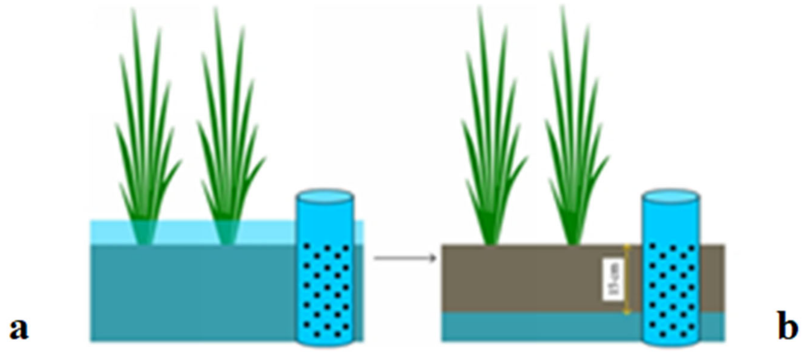

Figure 2. Schematic illustration of alternate wetting and drying practice in pot experiment: wetting condition (**a**) and soil drying condition (**b**).

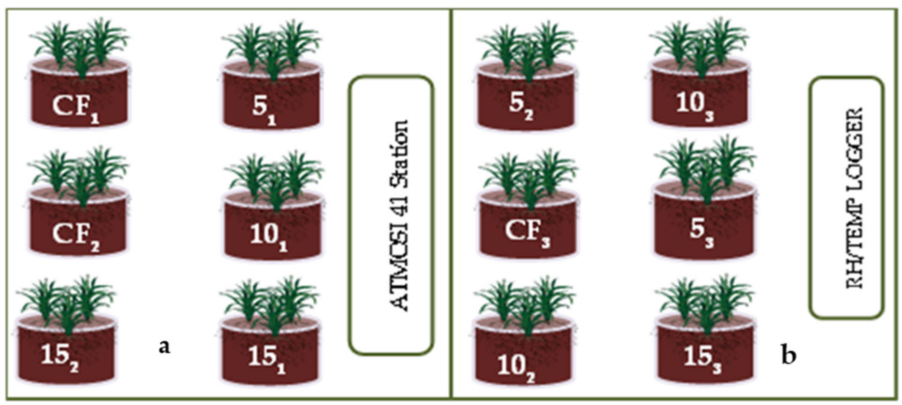

Figure 3. Experimental design and treatments: glass greenhouses (**a**) and (**b**) where CF is the control and 5, 10 and 15 are AWD5, AWD10 and AWD15 conditions; CF, continuous flooding irrigation; AWD, alternate wetting and drying irrigation practice. Each treatment has three replications.

2.2. Field Conditions and Measurements

The glass greenhouses were set under the same temperature conditions with the minimum and the maximum temperature of 20 °C and 30 °C, respectively, during cultivation. Rice variety, *Ikuhikari*, a short Japanese grain and widely grown rice cultivar [34], was directly seeded on 14 December 2021, and water regimes were applied 17 days after direct seeding (DAS). From direct seeding to harvest, the average pot seasonal rice water consumption varied from 78 to 120 L depending on different water regimes. During each irrigation, a known amount of water was applied (measured using graduated beaker) using a watering can. The stages of rice cultivation from direct seeding, fertilizer application, and irrigation application to harvest are summarized in Table 1. Water application in all regimes was stopped 4 days prior to harvesting. The total number of days from direct seeding to harvest was 105.

Table 1. Days of rice cultivation activities from direct seeding to maturity.

Stage	Direct Seeding	Start of Water Regimes	1st Fertilizer Application	2nd Fertilizer Application	Maturity Stage
DAS	1	17	30	64	105

2.2.1. Measurement of Growth, Tillers and Yield Survey

The crop height was measured on a weekly basis using a tape measure, and the number of tillers was counted manually in each treatment. The yield components (number of grain panicles, grain number, grain weight and brown/filled grains) were measured after harvest. The yield survey was performed by measuring rice grain number using rice counter and grain weight before and after dehusking. The rice pot was sampled each treatment and the number of grains (mature and immature) was measured. Mature rice grains were separated by sieving to separate them from immature ones. The grain numbers were recorded, and the percentage of mature grains was obtained from the number of total rice grains.

2.2.2. Crop Harvest Indexes and Biomass Dry Matter Content

The harvest index (HI) is one of the factors used to measure the difference between the potential and actual yield. For this research, HI was based on above-ground biomass and actual yields and estimated [27] using the formula below.

$$HI = {}^{Y}/_{AGB} \tag{1}$$

where *Y* is the yield (kg/ha) and *AGB* is the above-ground biomass accumulation (kg/ha).

Additionally, the fresh leaves were cut and separated from the rice stem after harvest to obtain the fresh weight. The stems and leaves were further cut into small particles and oven dried for 72 h at the temperature of 70 °C to avoid biomass burning. The total ratio of biomass dry matter content to fresh biomass was expressed as a percentage.

2.2.3. Water Productivity

Generally, water productivity is expressed as the total of irrigation water productivity (WP) and rainwater productivity (RWP), which are the total water (rain + irrigation) [35], expressed in kg/m^3; Y is the grain yield expressed in kg/ha. In this research, the rice's WP was obtained by dividing the average yield on the average season irrigation water consumed per pot in each treatment during the whole cultivation growth period. WP is an important index for the evaluation of irrigation water management [36].

$$WP = {}^{Y}/_{I} \tag{2}$$

where *Y* is the yield of rice (kg/ha), and *I* is the amount of irrigation water (m^3/ha).

2.3. Data Processing and Analysis

The data analysis was of variance (ANOVA), and this was performed in Microsoft Excel with comparative analysis using the Fisher man's pairwise comparison method [37]. The lowest significant difference (*LSD*) was obtained by Equation (3).

$$LSD = t_v, \alpha \sqrt{MS_{s(A)} \left(\frac{1}{S_\alpha} + \frac{1}{S_{\alpha^1}} \right)} \tag{3}$$

With an equal number of observations within the group, Equation (3) is simplified as Equation (4).

$$LSD = t_v, \alpha \sqrt{MS_{s(A)} S} \tag{4}$$

where α is the number of observations per treatment, $MS_{S(A)}$ is the mean square error within the group *A*, *t* is the *t*-statistics from the statistical *t*-distribution table, and v is the degree of freedom obtained from the same table.

To make the conclusion, the absolute value of the difference between means was compared with *LSD*. If the difference between means was found to be greater than the *LSD*, then it was recorded as a significant difference and vice versa.

3. Results

3.1. Effect of Water Regimes on Rice and Tiller Growths

Figure 4a shows the average crop height with different water regimes. There was a gradual difference in rice growth among different water regimes. Forty days after direct seeding, CF and AWD15 had small differences in crop height on AWD10 and AWD5. The crop height difference is attributed to changes in water regimes. At heading, the lowest crop height was noticed slightly in CF, AWD5 and AW10, while comparable height increments were observed in AWD15. In addition, crop heights at the grain filling and maturing stage were nearly the same under all water regimes.

In addition, tillering is an important trait in grain production, although the productivity of rice plants is highly dependent on the number of effective tillers with panicles bearing at least one filled grain rather than the total number of tillers [38]. Figure 4b shows the effect of different water regimes on crop tillers. Initially, the number of tillers was nearly the same under all the water regimes, although between 40 and 50 DAS, AWD15 and CF had a higher number of tillers compared to AWD5 and AWD10. Toward the end of the vegetative stage, to the grain filling, CF had a slightly higher number of tillers compared to all the AWD treatments. The water regimes did not significantly affect crop height and the number of tillers.

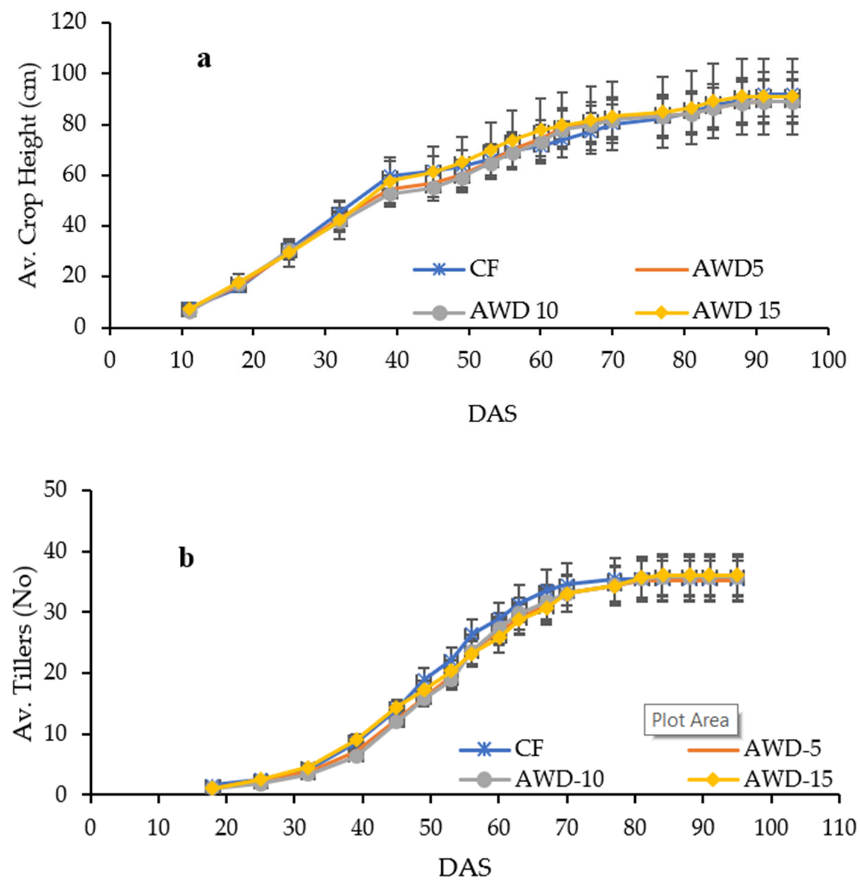

Figure 4. Average crop: height (**a**) and tilers (**b**), where Av. is the average, DAS is days after direct seeding, CF is the continuous flooding irrigation, and AWD is the alternate wetting and drying irrigation practice.

3.2. Effect for Irrigation Water Regimes on Yield and Yield Components

The results of crop yields, number of panicles, grain number and percentage of mature grains are shown in Figure 5a,b. There was no significant difference for the yields observed in all water regimes; however, CF (0.172 kg) had a slight difference of 0.028, 0.034 and 0.012 kg in the yields compared with AWD5, AWD10 and AWD15, respectively. In addition, CF and AWD15 had the same average number of tillers with a slight difference of six and eight tillers observed in AWD5 and AWD10.

On the other hand, grain maturity is an important factor in determining the optimum harvest time and affecting grain yields. Water regimes affected the number of grains and their maturity. The number of grains was highest in AWD5 with 7034 as compared to the other water regimes with 6601, 4371 and 5421, corresponding to CF, AWD10 and AWD15, respectively. The AWD5 and CF had a similar range of grains with a slight difference of 433 grains. In addition, the lowest number of 4371 grains was observed in AWD10. The percentage of mature of grains in AWD10 and AWD15 was the same. The highest percentage (76) of mature grains was observed in CF compared to 73 in AWD5 and 70 corresponding to AWD10 and AWD15.

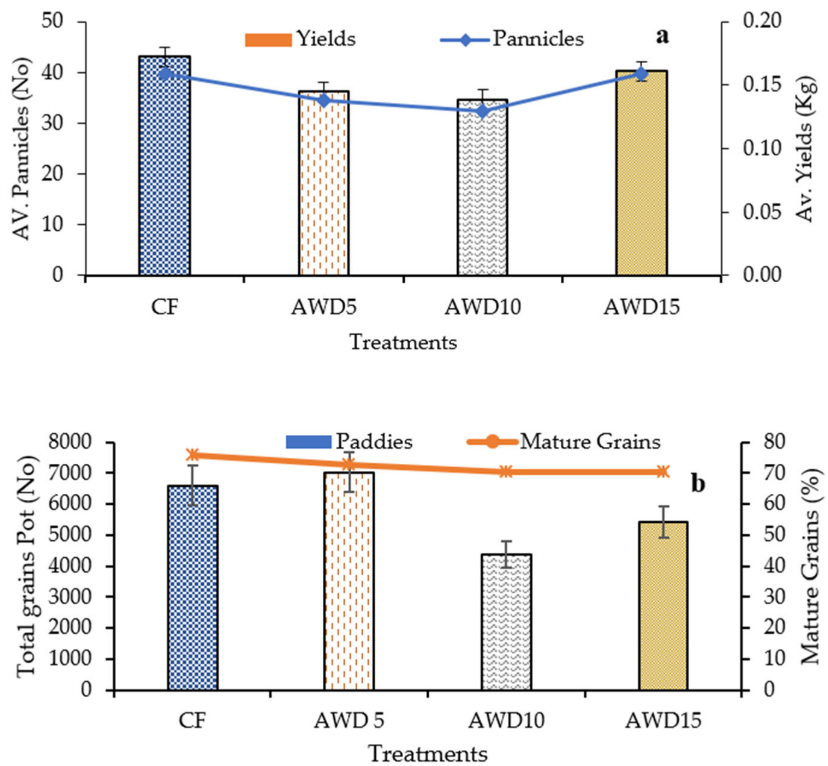

Figure 5. Crop: Average panicles and yields (**a**), and grain number and percentage of mature grains (**b**), with water regimes, where Av. is the average, CF represents continuous flood irrigation as control, and AWD represents alternate wetting and drying irrigation practice.

3.3. HI and Biomass Dry Matter Content with Different Water Regimes

Figures 6 and 7 show the crop HI and percentage of dry matter content under different water regimes, respectively. The HI values in all AWD water regimes range from 0.607 to 0.538 kg/kg, although CF had a slightly large HI value compared to AWD5, 10 and 15, respectively. Similarly, the percentage of dry matter in AWD5 and AWD10 was slightly higher than that of CF. The highest percentage of nearly 33% was observed in AWD5 and 10, while the lowest percentage of dry matter content of 25% was observed in AWD15.

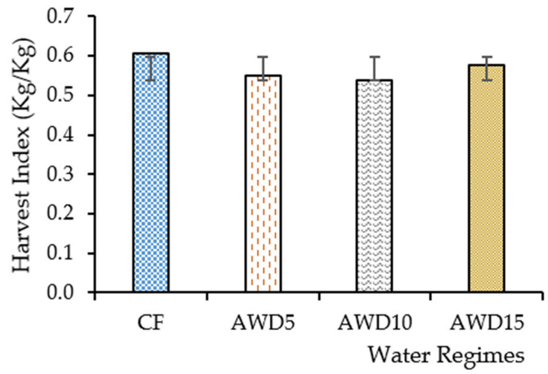

Figure 6. Crop harvest indexes under different water regimes.

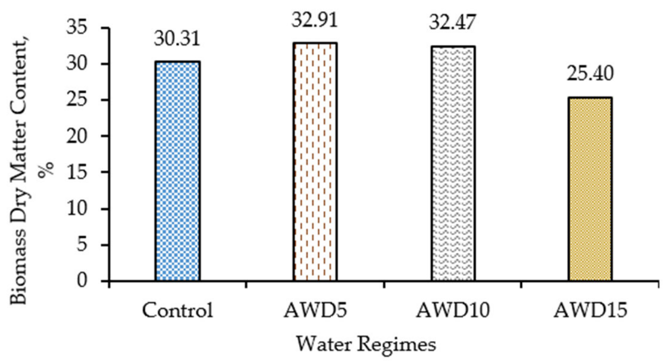

Figure 7. Percentage of biomass dry matter content under different water regimes.

3.4. Seasonal Water Use, Water Productivity and Water Saving

Table 2 summarizes the average seasonal pot water use and productivity with different water regimes. The seasonal water uses from direct planting to harvest represented 121, 78, 76 and 89 L under CF, AWD5, 10 and 15, respectively. The highest season water use was observed in CF (121 L) and the lowest was observed under AWD10 (76 L). On the other hand, the seasonal water use demonstrates water saving in AWD5, 10 and 15 conditions by 35, 37 and 26%, respectively. It was also observed that rice plants required more water during their mid to late vegetative growth stage; however, this depends largely upon local soil and climatic condition, as mentioned by Chapagain and Yamaji [39]. In addition, Figure 8 shows the cumulative changes in average pot water use with different rice growth stages. It was observed that at the vegetative stage, rice used nearly the same water amounts in all AWD conditions with the difference of 2.6, 4.4 and 2.6 L corresponding to AWD5, AWD10 and AWD15, respectively, compared to CF.

Table 2. Average seasonal pot water use and productivity.

Treatments	Av. Irrigation (L)	Wp (kg/m^3)	Water Saving (%)
CF	121	1.43	-
AWD5	78	1.86	35
AWD10	76	1.83	37
AWD15	89	1.81	26

Note: CF, continuous flood irrigation as control; Av., Average; AWD, alternate wetting and drying practice; Wp, water productivity.

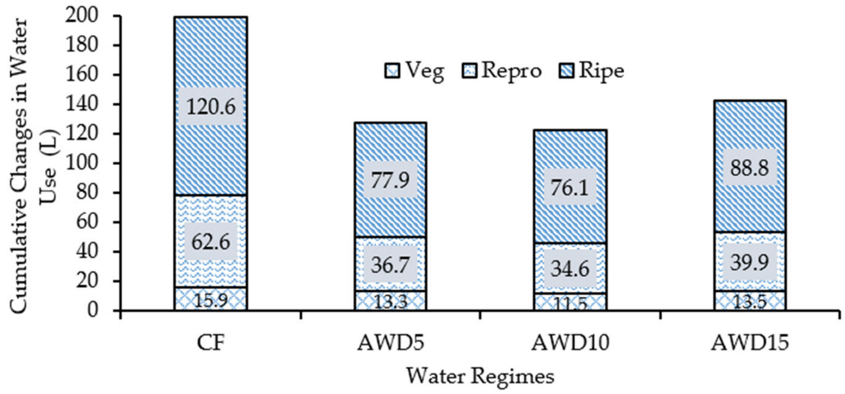

Figure 8. Cumulative change in average pot water use with rice growth stages. Where Veg represents the vegetative stage, Repro represents the reproductive stage, Ripe represents the ripening stage, CF represents continuous flood irrigation as control, and AWD represents the alternate wetting and drying irrigation practice**.**

4. Discussion

4.1. Impact of Irrigation Conditions on Rice Growths and Tillers

In AWD practice, paddy soils are subjected to periodic irrigation and drying conditions, which are related factors such as irrigation, air temperature, soil type and properties [40]. In this research, the water regimes were applied 17 days after seeding (DAS) and are in line with IRRI recommendations. The water application in different water regimes varied according to the rice growth stages. Water ponding depth varied from 2 to 4 cm, while its duration under all water regimes at the tillering to vegetative stage varied from 2 to 7 days, although this changed to 1 to 2 days under AWD conditions and even to a half-day in both CF and AWD conditions, at grain formation and maturity. Rice is sensitive to any severe water stress, and this was observed in plant height reduction at the end of booting to panicle initiation (AWD5 and AWD10) and maturity stage (AWD10). Any change in water application tended to induce drought stress, contributing to a decline in net photosynthesis and reduced growth through the inhibition of cell elongation or cell division [35]. Similarly, the induced short water stress in this research was observed with a difference in crop height and tiller numbers [41] in AWD conditions compared with CF between 49 and 70 DAS. Additionally, not all the tillers were developed to maturity (productive tillers). Some degenerate to become dormant when young and die later depending on environmental and nutritional conditions [42], affecting the final yields. The rate of the crop recovery due to re-water application depended on the soil conditions such as soil water, pre-drought intensity and duration [43] of soil drying, which was very short, causing visible water stress in all AWD conditions during the studied period. On the contrary, and due to the short soil drying periods in this study, crop growth and tillering were insignificantly affected by water regimes. This is in support with the research by Nguyen et al. [44], who compared various water-saving systems in rice and found an insignificant difference in tiller number among water regimes. The same study also suggested that tillering was less sensitive than other characteristics, such as plant height and leaf area.

4.2. Effect for Irrigation Treatments on Yield and Yield Components

Our results demonstrate that the yields, numbers of panicles and grains, and percentage of mature grains were not significantly affected by the water regimes. However, there were slight declines in the yields, grains and percentage of mature grains. Much of the induced invisible short water stress seems to have occurred due to water applications with different water regimes. This was not critical, since the amount of water application based on different regimes contributed to the infiltration rate that coincided in time with water uptake [35]. The availability of soil water conditions did not reach a critical point for the crops to develop a deeper root system as an adaptation measure but also due to the depth of the pots. The decline in the percentage of mature grains supports the findings of Kumar et al. [45], who indicated that the percentage of unfilled grains was significantly higher in sites that were affected by drought at the reproductive stage. Further research by Davantgar et al. [46] showed that any water stress at flowering causes flower abortion and an increase in unfilled grain percentage. This induces spikelet sterility or grain filling delay, leading to a high unfilled grain percentage, which further reduces the overall grain yield, as observed in AWD10 and AWD15. Additionally, the delay in plant growth, due to any induced water stress during panicle initiation, delays the heading rate, decreasing the panicle number and grain formation [39]. Any water stress at panicle initiation is more destructive to panicle number biomass dry mass and total grains, irrespective of the cultivars, resulting in a drastic decrease per hectare in paddy yield as noted by Akram et al. [47]. However, in this research, the number of panicles for each water regime produced similar results though decreased average yields with the AWD conditions.

4.3. Harvest Indexes and Biomass Dry Matter Content with Different Treatments

The water regimes had an insignificant effect on the HI of the rice as observed by HI values of 0.607, 0.550, 0.538 and 0.576 Kg/Kg corresponding to CF, AWD5, AWD10 and AWD15, respectively. This could have been due to the similarity in morphological aspects of vegetative growth such as same time of head initiation, duration of grain heading, biomass accumulation in the formation of stems, leaves at heading and decline in grain filling affecting the final yields in the same rice cultivars as noted by Elkheir et al. [48], which is the similar case in this research. The study by Chen et al. [49] on the rice cultivars also showed the similarity in the change of stem biomass between aerobic rice cultivars and little increase after the booting stage, whereas there were differences in duration from the booting stage to the heading stage. Other research indicates that seed priming reported its effect on harvest index and reproductive stage components. Its attributes may be due to pre-germination metabolic activities that make the seed ready for radical protrusion, leading to good crops establishment [48,50]. Similarly, our results indicated that the biomass dry matter content was not affected significantly. However, the highest percentage of biomass dry matter was produced under AWD5 (33%), which was followed by AWD10 (32%). Furthermore, the lowest biomass dry matter content was observed in AWD15 (25%). Therefore, the application of fertilizer at the appropriate rate and time with different water regimes can improve above-ground biomass and can increase rice yield, as observed by Haung et al. [51], since the effects of water and nutrients on crop growth, yield and HI are interactive [28]. Our findings also demonstrated the potential to increase the HI of rice with directly seeding.

4.4. Seasonal Water Use, Water Productivity and Water Saving

Generally, high irrigation WP was produced in all AWD conditions, with the highest WP (1.86 kg/m^3) observed in AWD5, which was followed by AWD10 and AWD15 with 1.83 and 1.81 kg/m^3, respectively, compared to CF (1.43 kg/m^3). However, the lowest yield reduction (0.033 kg) and highest immature grains (30%) was observed in AWD10, indicating that 0.033 kg of yield was lost for saving 1 m^3 of water compared with CF. Similarly, research on different water regimes by Zhang et al. [52] observed a significant increase in grain yield and water use efficiency when the soil water potential was reduced to 25 kPa in AWD. This indicates that a drying period with AWD water regimes is the major factor affecting paddy yield, although soil drying to 25 kPa is beneficial to grain growth during grain filling. Based on the AWD conditions, the soil drying varied from 2 to 5 days at the crop development stage and 0.5 to 2 days at the reproductive and ripening stages. On the other hand, an increase in water use in all water regimes was observed toward the end of the vegetative stage to ripening, as seen in Figure 8. In addition, AWD15 had high seasonal water use as compared to other AWD regimes due to increased water use in different pots with the same treatment due to changes in plant morphological activities in the vegetative and ripening stages. It was observed that irrigation water application in paddies with AWD conditions must be carried out as soon as water drops the required soil depth to avoid any induced water stress, which may affect rice productivity. AWD15 was accepted as the best irrigation practice among the other different irrigation management practices with a 26.3% reduction in water use and only a 6.7% reduction in grain yield compared to the CF, AWD5 and AWD10 conditions.

5. Summary

The conclusions drawn from this study are:

- The grain yield of paddy rice did not reduce significantly in AWD conditions. The reduction is ineffective so long as the soil moisture is in the range of readily available water for the rice depending on the soil type and soil hydraulic conditions.
- Any induced water stress due to different water regimes especially at panicle and grain formation can delay rice growth, causing a difference in the number of tillers panicles and yields
- AWD has the potential to improve irrigation water productivity with an insignificant difference in yields and increase in the HI of paddy rice. Timely water application and fertilizers can contribute to yields, biomass and HI.
- AWD15 was accepted as the best irrigation practice due to a 26.34% reduction in water use and only a 6.40% reduction in grain yield compared to the control continuous flooding treatment.

The findings of the present study provide data reference from glass greenhouse conditions for the theoretical scientific knowledge and understanding of safe AWD practice. This is support for water management and water saving in paddy rice cultivation with safe AWD practice applied throughout the whole cultivation period in countries facing water shortages.

Given that our study was conducted in glass greenhouse conditions, it is important to conduct this research in in situ field conditions. Water application by both matric potential and FWL with safe AWD practice throughout the whole cultivation period on different paddy soil types should be evaluated. Effects on water, crop productivity and clay physical properties such as hydraulic conductivity, expansively and plasticity should be further explored.

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