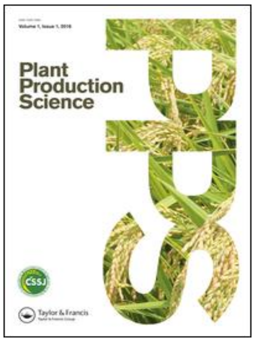


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REGULAR PAPER

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# Utilizing rainfall and alternate wetting and drying irrigation for high water productivity in irrigated lowland paddy rice in southern Taiwan

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**ABSTRACT**

Taiwan's average annual rainfall is high compared to other countries around the world; however, it is considered a country with great demand for water resources. Rainfall along with alternate wetting and drying irrigation is proposed to minimize water demand and maximize water productivity for lowland paddy rice cultivation in southern Taiwan. A field experiment was conducted to determine the most suitable ponded water depth for enhancing water saving in paddy rice irrigation. Different ponded water depths treatments ($T_{2\,cm}$, $T_{3\,cm}$, $T_{4\,cm}$ and $T_{5\,cm}$) were applied weekly from transplanting to early heading using a complete randomized block design with four replications. The highest rainwater productivity (2.07 kg/m$^3$) was achieved in $T_{5\,cm}$ and the lowest in $T_{2\,cm}$ (1.62 kg/m$^3$). The highest total water productivity, (0.75 kg/m$^3$) and irrigation water productivity (1.40 kg/m$^3$) was achieved in $T_{2\,cm}$. The total amount of water saved in $T_{4\,cm}$, $T_{3\,cm}$ and $T_{2\,cm}$ was 20, 40, and 60%, respectively. Weekly application of $T_{4\,cm}$ ponded water depth from transplanting to heading produced the lowest yield reduction (1.57%) and grain production loss (0.06 kg) having no significant impact on yield loss compared to $T_{5\,cm}$. Thus, we assert that the weekly application of $T_{4\,cm}$ along with rainfall produced the best results for reducing lowland paddy rice irrigation water use and matching the required crop water.

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## Introduction

Global agriculture is faced with the tremendous challenge of providing enough food for a growing population under increasing water scarcity. Fresh water for irrigation is becoming scarce because of population growth, increasing urban and industrial development, and the decreasing availability resulting from pollution and resource depletion (Bouman, 2007; Chapagain & Riseman, 2011; Edward & David, 2008; Thakur et al., 2011). The world food security remains largely dependent on irrigated lowland rice which is the main source of rice supply (Bouman, 2007; Yang & Zhang, 2010). Irrigated rice production is the largest consumer of water in the agriculture sector, and its sustainability is threatened by increasing water shortages (Thakur et al., 2011). Agriculture water productivity directly affects crop productivity; therefore, various water-saving techniques and methods have been developed for rice producers to minimize water demand and maintain acceptable yield.

One of the most widely promoted water-saving technique for rice is alternate wetting and drying (AWD) irrigation (Cabangon et al., 2011; Chu et al., 2014; Yao et al., 2012), it has been considered a novel water-saving technique which has been adopted in many countries such as China, Bangladesh, India, and Vietnam (Bouman, 2007; Yang et al., 2007; Yao et al., 2012; Zhang et al., 2009). In AWD, irrigation water is applied to achieve intermittent flooded and non-flooded soil conditions. The frequency of irrigation and duration of non-flooding can be determined by (a) re-irrigating (to achieve flooded conditions) after a fixed number of non-flooded days (b) when a certain threshold of soil water potential is reached (c) when the ponded water table level drops to a certain level below the soil surface (d) when cracks appear on the soil surface or (e) when plants show visual symptoms of water shortage (Peng & Bouman, 2007). Commonly, irrigation is applied to obtain 2–5 cm ponded water depth after a predefined number of days (ranging from 2 to 7) have passed following disappearance of ponded water. It has been reported that compared to continuously flooded conditions, AWD irrigation can maintain or even increase grain yield (Nyamai et al., 2012; Yang et al., 2007; Yao et al.,

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2012; Zhang et al., 2009). On the contrary B. A. M. Bouman and Tuong (2001) and Belder et al. (2004) emphasized that yield penalty is commonly observed under AWD compared with continuously flooded-irrigated rice but generally, AWD increased water productivity with respect to total water input because the yield reduction was smaller compared to the amount of water saved (Yao et al., 2012).

Irrigated rice requires effective water management during the entirety of the crop cycle as rice is very sensitive to water stress and attempts to reduce water may result in yield reduction which may also threaten food security. In contrast to other crops, it is particularly more sensitive to water stress especially in critical growth stages such as panicle initiation, anthesis, and grain filling (Akram et al., 2013; Davantgar et al., 2009; Sarvestani et al., 2008). Drought stress contributes to various plant changes including photosynthetic rate, pigment degradation, relative water content (RWC), and growth reduction prior to senescence (Cattivelli et al., 2008; Tuna et al., 2010).

Rice is a very important and valuable crop in Taiwan with a total yield of more than 1.73 million tonnes from 271,077 hectares of land for a production value of NT$41.48 billion (about US$1.37 billion) in 2014 (The Republic of China Year Book, 2014). Cropping seasons for paddy rice in Taiwan is from February to July, and August to December (Liou et al., 2015). Taiwan is located in a rainy region and has an annual average precipitation of (2500 mm) which is higher than that of the world average (834 mm) however; it is considered a country with great water demand (Liou et al., 2015). This is due to the fact that only a small portion of the water brought by precipitation can be stored over land as most of the water flows directly into the sea through various rivers in response to steep mountain terrain. The annual water consumption in Taiwan is 17,064 million m$^3$, of which 11,088 million m$^3$ or 65% is consumed by irrigation (Lee & Huang, 2014). Throughout the year, 78% of the rainfall occurs from May to October in Taiwan, but it reaches up to 90% in the southern region (Hsiao, 2000). In this regard, the maximization of water resources is imperative and emphasis must be placed on making efficient use of agricultural water.

The combined effects of rainfall and irrigation especially in southern Taiwan may reduce irrigation cost and increase output, and can particularly be effective in the reproductive and grain-filling stages where rice is more sensitive to water stress. Therefore, the objectives of this research is to apply AWD irrigation while simultaneously maximizing rainfall to determine the most effective ponded water depth leading to optimum water uptake and low losses. Water productivity and water saving will be determined since the reduction in irrigation cost is also sought in rice production. This approach takes advantage of the combined effects of rainwater and irrigation during the growth stages and therefore it is expected that AWD will be optimized, through the use of strategic irrigation management and maximization of rainwater. Such approach is less documented in southern Taiwan and hence the reason for the current research.

## Materials and methods

### *Experimental site and trial design*

The research was conducted from February to June 2015 in the irrigation research and education field at the National Pingtung University of Science and Technology in southern Taiwan, located at 22.39° (N) latitude, 34.95° (E) longitude and 71 m above sea level. The soil type was loamy (27% of sand and 24% of clay) with a wilting point of 15% volume; field capacity 30.5% volume; saturation 42.9% volume; bulk density 1.40 g/cm$^3$; matric potential 11.09 bar; and hydraulic conductivity 57 mm/hr. The experimental design was a randomized complete block design with four replications and four water treatments. Each plot was 6 m long, 1 m wide, with a total area of 6 m$^2$, and 0.3 m soil bed height. The spacing between plots and between blocks was 1 m. Ponded water depths were applied at 5, 4, 3, and 2 cm representing $T_{5\ cm}$, $T_{4\ cm}$, $T_{3\ cm}$, and $T_{2\ cm}$, respectively.

Twenty-five-days old seedlings were obtained from the seed nursery and were manually transplanted on 1 February. Three seedlings were transplanted at hill spacing 25 cm between hills and 20 cm between rows (20 plants m$^{-2}$). Fertilizer ($N{:}P_2O_5{:}K_2O$) was applied at a ratio of 12:18:12 with a rate of 170 kg/ha at basal, mid-tillering, and panicle initiation. Pests were controlled by pesticide application and weeds manually. Irrigation treatments were applied immediately after transplanting and the irrigation interval was scheduled at 7 days. Applied water volume to reach the desired ponded depths was obtained using the following equation from FAO (1985) and cited by Kima et al. (2014).

$$IR = A \times h \times 10^3 \tag{1}$$

where IR is the amount of irrigation water (L) for a desired depth above the soil surface, $A$ is the surface area of the plot (m$^2$), and $h$ is the desired ponded water depth above the soil surface (m). The final irrigation treatment was applied during heading stage on 15 May, thereafter the rain was frequent and crop was subjected to rain-fed conditions.

### *Soil water content and soil trend analysis*

The soil water content was measured every 2 days from 1 month after transplanting to 1 month before harvest using the gravimetric method. Soil samples were collected using an auger, in three different locations within each plot at 15 and 25 cm depth. The soil was immediately weighed, and dry weight was obtained after oven drying at 105 °C for 24 h. The soil water content per unit was calculated using the following equation (Kima et al., 2014).

$$SW = \frac{100 \times (\text{fresh weight} - \text{dry weight}) \times \gamma_s}{\text{Dry weight}} \quad (2)$$

where SW is the soil water content (mm) soil depth and $\gamma_s$ is the soil bulk density (g/cm$^3$). The soil water trend was analyzed by determining the soil water content at saturation level, field capacity, wilting point, and stress threshold using Equations (3)–(6) (Allen et al., 1998).

$$SW_{Sat} = 1000(SAT)xZ_r \quad (3)$$

$$SW_{FC} = 1000(FC)xZ_r \quad (4)$$

$$SW_{WP} = 1000(WP)xZ_r \quad (5)$$

$$SW_{ST} = 1000(1 - P)SatxZ_r \quad (6)$$

where $SW_{Sat}$, $SW_{FC}$, $SW_{WP}$, and $SW_{ST}$ are soil water content (mm) at saturation, field capacity, wilting point, and stress threshold level, respectively. Sat, FC, and WP are the soil water content at saturation, field capacity and wilting point, respectively in percentage of volume. P is the fraction of water that can be depleted before moisture stress occurs and represent 20% of the saturation for rice crop; $Z_r$ is the sample collection depth (m).

### *Assessment of agronomic parameters*

A square meter quadrant which constitutes 20 individual hills was established in the center of each plot to assess plant height and tiller number at panicle initiation and heading stage. Plant height was measured from the base to the tip of the highest leaf while tillers were counted individually per plant.

Data for leaf area and leaf area index (LAI) was measured at panicle initiation and calculated following the methods of (Tadesse et al., 2013; Yoshida, 1981).

$$\text{Leaf area}\left(\text{cm}^2\right) = L \times W \times K \quad (7)$$

where, *L* is leaf length; *W* is maximum width of the leaf and K is a correction factor of 0.75.

Leaf Area Index (LAI):

$$LAI = \frac{\text{sum of the leaf area of all leaves}}{\text{ground area of field where the leaves have been collected}} \quad (8)$$

Five (5) hills from each replicate were randomly selected outside the squares for root and biomass per hill assessment at panicle initiation. This was done using an auger 10 cm diameter to remove soil of 20 cm depth from selected hills. A uniform soil volume of 1570 cm$^3$ was excavated to collect root samples for all treatment. Roots were carefully washed and removed from uprooted plants. Root volume was measured by water displacement method of putting all the roots in a measuring cylinder and getting the displaced water volume (Ndiiri et al., 2012). Root depth was obtained by direct manual measurements of top root using a ruler against a millimeter paper. Roots dry weight and dry biomass per hill were obtained after oven drying at 70 °C for 24 h.

### *Leaf chlorophyll content and RWC*

A chlorophyll meter (model SPAD-502, MINOLTA, Japan) was used to determine leaf chlorophyll content. Good correlations have been found between the SPAD-502 value and extractable leaves chlorophyll content in several species although specific calibration is always recommended (Marenco et al., 2009; Markwell et al., 1995). At panicle initiation and heading stage, 12 hills per plot were selected throughout the diagonals and median, and the 12 uppermost fully expanded leaves were selected from these random hills to analyze the variability in chlorophyll content among treatments with three observations made per leaf. Analysis of leaves sampling patterns done by Chapman and Barreto (1997) and Kima et al. (2014) showed that at least four leaves per plot are needed, with several observations per leaf. Then, the average of these three readings was used to represent the leaf chlorophyll content.

The leaf RWC was calculated from fresh weight (FW), dry weight (DW), and turgid weight (TW).

$$RWC(\%) = [(FW - DW)/(TW - DW)] \times 100 \quad (9)$$

### *Measuring of yield and yield components*

To analyze the heading rate, daily headed panicle numbers were determined in each plot from appearance of the first panicle until 50% heading were obtained within each plot. At harvest, yield components (panicle number per hill, panicle length, and panicle weight, grain number per panicle, grain weight per panicle, and filled grain per panicle) were obtained from inside the square. Panicles were cut at the base, separated from the straw, and the number was determined for each hill. Panicles from each plot were individually measured to determine maximum and minimum length. The range was calculated, and the class interval was obtained by dividing the range by 3 (desired number of classes). Three length classes were determined per plot and panicles were arranged accordingly. Five panicles

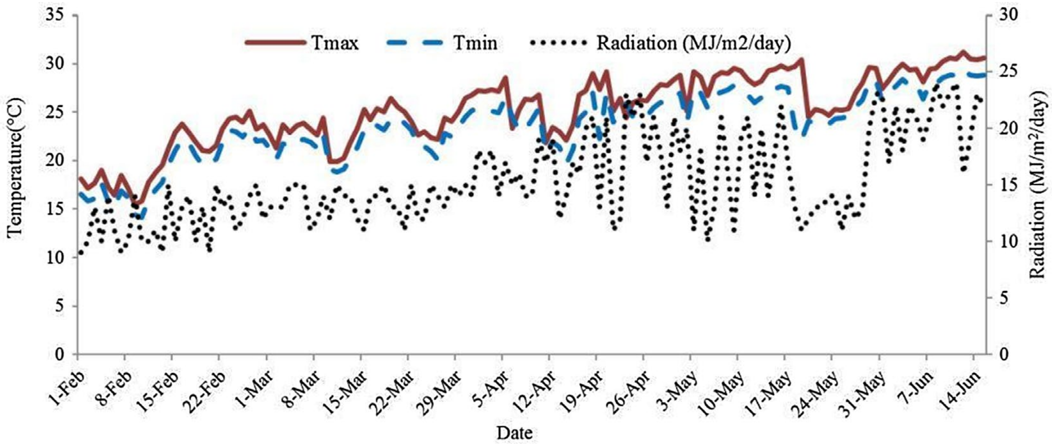


**Figure 1.** Daily maximum and minimum temperatures and radiation during the crop cycle.

were randomly selected from each class and the length and weight were measured. The same sampled panicles were individually hand threshed and grain number per panicle was determined. All plants in the squares were harvested for grain yield per unit area (tha$^{-1}$) of determination. Three samples of harvested grains were randomly picked from each replicate and the dry weight was determined. Grains weight per panicle, and grain yield was obtained at a constant weight after oven drying at 70 °C for 72 h. The grain yield for unit area was then adjusted at the standard moisture content of 14%. Five samples of 1000 grains were taken from the total grains production of each plot and weighted for 1000 grains weight determination. Filled spikelets from these samples were separated from unfilled spikelets using a seed blower for 2 mm. The percentage of filled grain was calculated, on mass basis, as the ratio of filled grains weight out of the total grains weight multiplied by 100. Fifteen samples were considered per treatment. The dry biomass per hill from the harvested plants was determined after oven drying at 70 °C for 24 h, and the total straw weight (tha$^{-1}$) was calculated accordingly. The harvest index (HI) was calculated as the ratio of total grain yield to the total straw yield.

### Water productivity assessment

The total water productivity (TWP), irrigation water productivity (IWP), and rainwater productivity (RWP) are the total water (rain + irrigation), irrigation water, and rainwater productivity, expressed in kg m$^{-3}$; Y is the grain yield expressed in kg ha$^{-1}$. TWU, IWU, and RW are the total water, irrigation water and rainwater used, respectively, expressed in m$^3$ ha$^{-1}$ and were calculated according to Equations (10)–(12) (Pereira et al., 2012).

$$TWP = \frac{Y}{TWU} \quad (10)$$

$$IWP = \frac{Y}{IWU} \quad (11)$$

$$RWP = \frac{Y}{RW} \quad (12)$$

Grain production losses were calculated considering the yield of $T_{5\,cm}$ as a reference, and water-saving impact was defined as the grain production lost by saving one unit of irrigation water. The water-saving impact was obtained by dividing the quantity of grain lost per hectare by the amount of water saved (m$^3$/ha).

### Data analysis

The statistical analysis applied on the data includes the analysis of variance using SPSS 22 software. The significance of the treatment effect was determined using *F*-test and means were separated through Turkey's test at 0.05.

## Results

### Agro-hydrological conditions and soil water during the growing season

The hydrological data were recorded at the National Pingtung University of Science and Technology, Agro-Meteorological station. Figure 1 highlights the daily maximum and minimum temperatures and radiation during the crop cycle. Maximum temperatures ranged from 16.4 to 31.1 °C with a mean value of 25.1 °C, and the minimum temperature from 14.1 to 28.8 °C having a mean value of 23.5 °C, meanwhile the radiation values ranged from 9.1 to 24.8 MJ/m$^2$/day. The low values for these parameters were observed in February while the high values were observed in June.

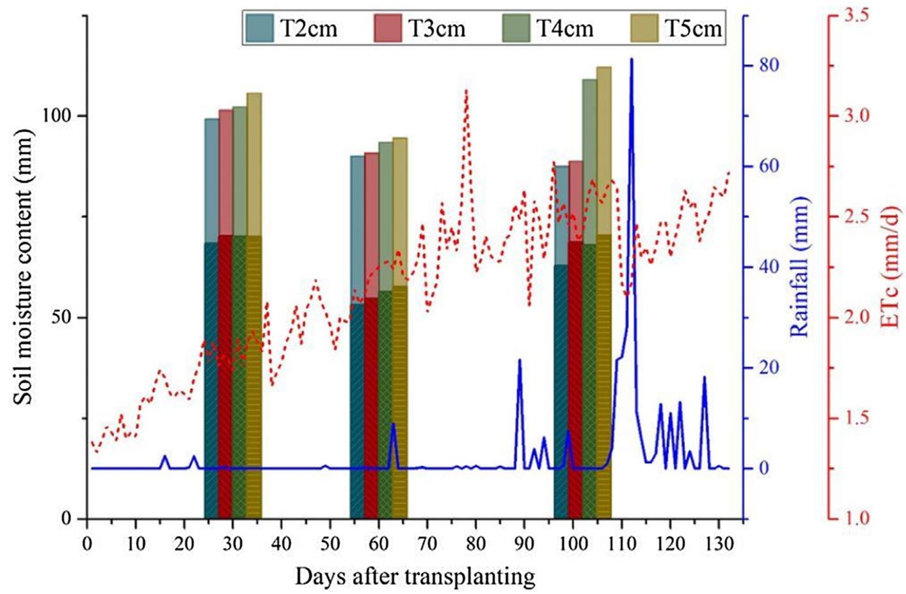


**Figure 2.** Rainfall, ETc, and soil moisture content at 15 and 25 cm depths.

Figure 2 illustrates the rainfall and ETc throughout the crop cycle, and the soil water content at 15 and 25 cm depths at 30, 60, and 100 days after transplanting. Daily rainfall ranged from 0 to 81.3 mm with monthly recorded values (February, March, April, May, and June) of 5.2, 0.9, 11.2, 229.2, and 30.1 mm, respectively. Slight and inconsistent rainfall occurred towards the end of April coincided with the final stages of panicle initiation and early heading, however, rainfall was more frequent and consistent from the second week of May onwards. According to the growth stages, 62 $m^3$/ha of rain was recorded during the vegetative growth stage (February–March), 509 $m^3$/ha during panicle initiation (April to 12 May), and 2197 $m^3$/ha from heading (12 May) to harvest (16 June). During the vegetative stage, rainfall represented 3.87, 2.58, 1.93, and 1.55% of irrigation water applied in treatments $T_{2\,cm}$, $T_{3\,cm}$, $T_{4\,cm}$, and $T_{5\,cm}$, respectively. From panicle initiation to heading, it represented 42.41, 28.27, 21.21, and 16.96% of the same treatments. Plants were almost entirely grown under irrigation at the vegetative stage; on the contrary, they were subjected to both irrigation and rainfall during panicle initiation and almost exclusively grown under rain-fed condition from heading to harvest. The highest rainfall contribution throughout the crop cycle occurred from heading to harvest

The ETc was obtained by multiplying ETo per adjusted Kc (Allen et al., 1998). Crop evapotranspiration varied along the crop cycle and ranged from 1.33 to 3.12 mm/day with the lowest observed value in February (vegetative stage) and the highest observed value in April (panicle initiation). From panicle initiation up to the onset of harvest the crop, water demand was above 2 mm/day.

The soil analysis was performed from the vegetative to heading stage during the crop cycle (Figure 3(a) and 3(b)). Soil water content reached its maximum every 2 days after irrigation and then a sharp decline occurred until the next irrigation. $T_{5\,cm}$ produced the highest soil moisture throughout the crop cycle at 15 and 25 cm sampling depths. Soil moisture varied according to irrigation treatments but was usually between soil stress thresholds and/ or above soil saturation level for all water treatments during the vegetative stage. At 25 cm depths, the values for $SW_{Sat}$, $SW_{FC}$, $SW_{WP}$, and $SW_{ST}$ were 85.80, 76.25, 37.50, and 107.25, respectively and 64.35, 45.75, 22.50, and 51.48 at 15 cm depths. $T_{2\,cm}$ normally produced the lowest soil moisture content values, but was never below the soil stress threshold during the vegetative stage whilst the values for $T_{4\,cm}$ and $T_{3\,cm}$ were frequently between highest and lowest water treatments. At panicle initiation, soil moisture was repeatedly below the soil stress threshold level at 15 and 25 cm sampling depths in $T_{2\,cm}$. The lowest recorded value at 15 and 25 cm depths were 46.2 and 79.4 mm. Low values below the soil stress threshold level were recorded twice at 15 cm depths for $T_{3\,cm}$ and $T_{4\,cm}$ and once at 25 cm depths for $T_{3\,cm}$. The mean soil moisture content at 15 cm depth was 62.51, 64.94, 65.77, 66.73 mm, and 93.51, 95.24, 102.32, and 104.58 mm at 25 cm for $T_{2\,cm}$, $T_{3\,cm}$, $T_{4\,cm}$, and $T_{5\,cm}$ (Figure 4). From 15 May onwards rainfall was frequent and irrigation was suspended as the soil water content was within the soil saturation range in all treatments.

### *Crop growth*

The crop growth parameters of plant height and tiller numbers presented in Table 1 indicate that plant height

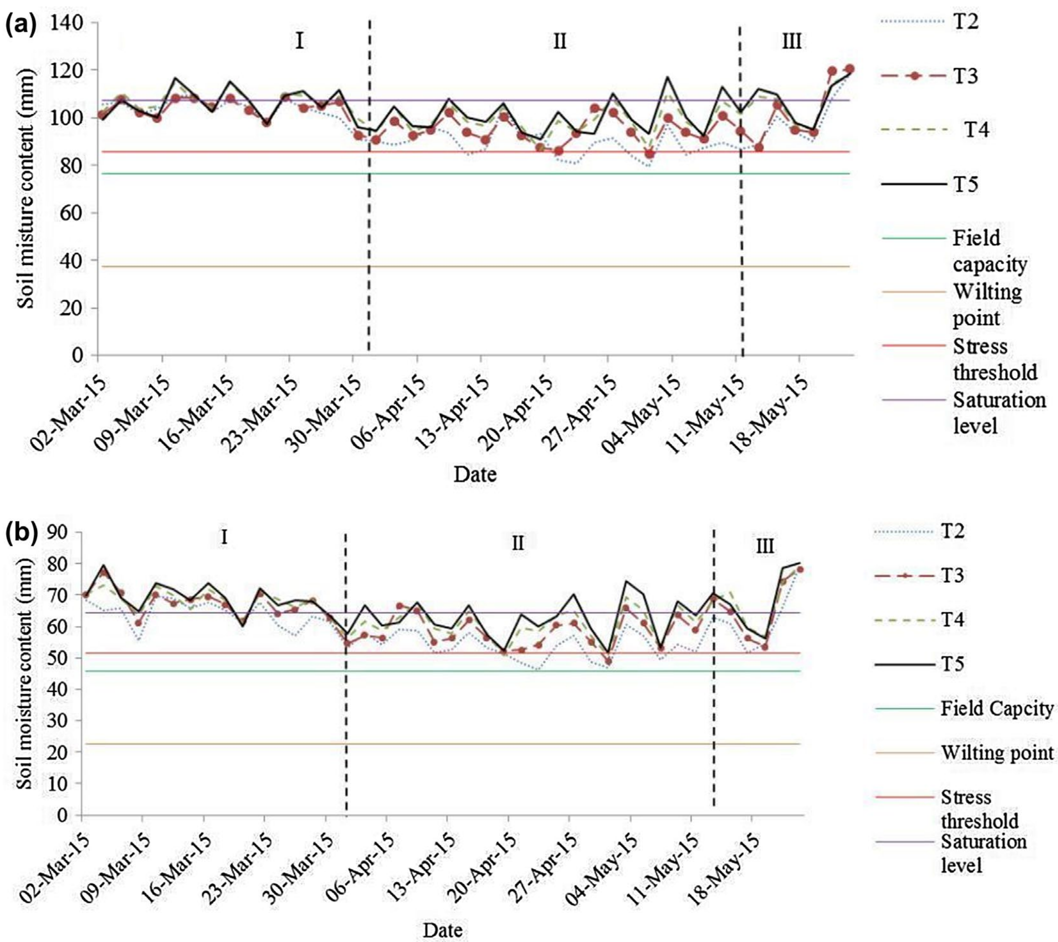


**Figure 3.** (a) Soil moisture trend at 25 cm (a) at vegetative (I), panicle initiation (II), and heading stage (III). 22 × 11 mm, (b) Soil moisture trend at15 cm (b) at vegetative (I), panicle initiation (II) and heading stage (III).

**Table 1.** Effects of water treatment on plant height and tiller numbers and LAI.

| | Panicle initiation | | | Heading | |
|---|---|---|---|---|---|
| Treatments | Plant height (cm) | Tiller numbers | Leaf area index | Plant height (cm) | Tiller numbers |
| T5 | 71.88$^{a}$ | 14.64 | 2.36$^{a}$ | 86.68$^{a}$ | 19.72 |
| T4 | 70.12$^{ab}$ | 13.93 | 2.03$^{b}$ | 84.77$^{ab}$ | 19.82 |
| T3 | 68.97$^{b}$ | 14.16 | 1.96$^{b}$ | 84.17$^{ab}$ | 19.32 |
| T2 | 68.65$^{b}$ | 13.28 | 1.65$^{c}$ | 83.32$^{b}$ | 18.75 |
| P | * | ns | * | * | ns |

*Mean with columns not followed by the same letter (a,b,c) is significantly different at $p < 0.05$ level by Turkey's test; *ns:* not significantly different.

was significantly affected by water treatments at panicle initiation and heading stage for $T_{2\,cm}$. Low plant heights were notable in lower water treatments, with $T_{2\,cm}$ and $T_{3\,cm}$ showing significant height difference compared to $T_{5\,cm}$ at panicle initiation. At heading, the lowest plant height was recorded in $T_{2\,cm}$, while comparable heights were observed among $T_{5\,cm}$, $T_{4\,cm}$, and $T_{3\,cm}$. Water restrictions at panicle initiation decreased average plant height by 4.70, 4.21, and 2.50%, while at heading, plant height was reduced by 4.03, 2.98, and 2.25% in $T_{2\,cm}$, $T_{3\,cm}$, and $T_{4\,cm}$, respectively. No significant differences were observed for tiller numbers among water treatments, however the smallest tillers and the least tiller numbers were observed in $T_{2\,cm}$. The LAI was significantly lower at panicle initiation when compared to $T_{5\,cm}$ and reduced by 43.04, 20.40, and 16.25% for $T_{2\,cm}$, $T_{3\,cm}$, and $T_{4\,cm}$ respectively.

### *Dry biomass, root dry weight, root depth, and root volume*

The results of dry biomass and root parameters are shown in Table 2. No significant differences were observed for dry biomass, root volume, and root dry weight in $T_{3\,cm}$, $T_{4\,cm}$, and $T_{5\,cm}$ however, there were significant differences noted between $T_{5\,cm}$ and $T_{2\,cm}$. Root depths were comparable for all treatments with no significant differences observed. Root dry weight and root volume were significantly higher for $T_{5\,cm}$ when compared to $T_{2\,cm}$, but results were comparable among $T_{2\,cm}$, $T_{3\,cm}$ and $T_{4\,cm}$ with high values observed in the higher water treatments.

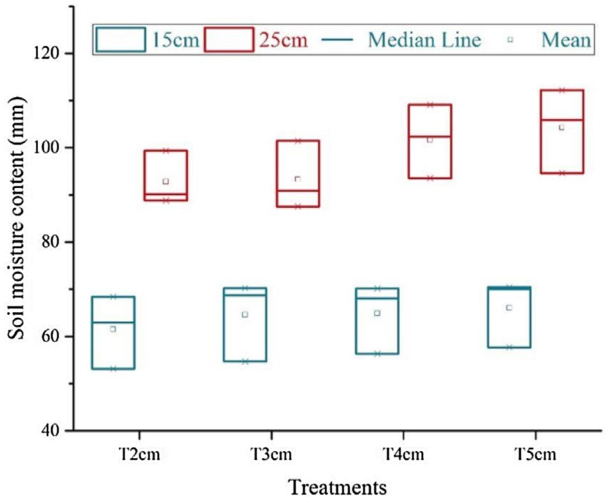


**Figure 4.** Mean soil moisture content during the crop cycle.

**Table 2.** Effect of water treatment on dry biomass, root dry weight, root depth, and root volume at panicle initiation.

| Treatments | Dry biomass (g/hill) | Root dry weight (g/hill) | Root depth (cm) | Root volume ($cm^3$) |
|---|---|---|---|---|
| T5 | 28.80[a] | 14.48[a] | 17.10 | 21.00 [a] |
| T4 | 26.71[ab] | 13.04[ab] | 16.89 | 20.30[ab] |
| T3 | 28.85[a] | 10.94[ab] | 16.44 | 17.40[ab] |
| T2 | 22.71[c] | 9.33[b] | 15.56 | 15.15[b] |
| P | * | * | ns | * |

*Mean with columns not followed by the same letter (a,b,c) is significantly different at $p < 0.05$ level by Turkey's test; ns: not significantly different.

## *Leaf chlorophyll content and RWC*

Leaf chlorophyll content and leaf RWC (Table 3) were influenced by water treatments and produced the lowest value in $T_{2\ cm}$, but results were similar to $T_{3\ cm}$ and $T_{4\ cm}$ at panicle initiation. Water decreased leaf chlorophyll content at panicle initiation by 6.99% and 6.67% in $T_{2\ cm}$ and $T_{3\ cm}$, respectively. Significant differences were not observed in chlorophyll content and leaf RWC at the heading stage.

## *Effect of water treatment on yield components and grain yield components*

Daily headed panicle and panicle emergence were impacted by water treatments, Figure 5. Panicle numbers in T5 $_{cm}$ was significantly higher, and emergence was faster compared to other treatments. The effect of water treatment on average panicle reduction rate per square meter was 155, 214, and 443% in, $T_{4\ cm}$, $T_{3\ cm}$, and $T_{2\ cm}$ compared to $T_{5\ cm}$. Similar results were observed for average panicle number per hill, average panicle length, and average panicle weight (Table 4), however average panicle weight decreased with the lowest water treatment.

**Table 3.** Chlorophyll content and leaf RWC subjected to water treatments

| | Panicle Initiation | | Heading | |
|---|---|---|---|---|
| Treatments | Chlorophyll content | RWC | Chlorophyll content | RWC |
| T5 | 46.85[a] | 70.43[a] | 44.50 | 85.77 |
| T4 | 45.34[ab] | 65.02[ab] | 43.43 | 85.15 |
| T3 | 43.92[b] | 62.57[b] | 44.16 | 82.93 |
| T2 | 43.61[b] | 60.05[c] | 43.72 | 84.90 |
| P | * | * | ns | ns |

*Mean with columns not followed by the same letter (a, b, c) is significantly different at $p < 0.05$ level by Turkey's test; ns: not significantly different.

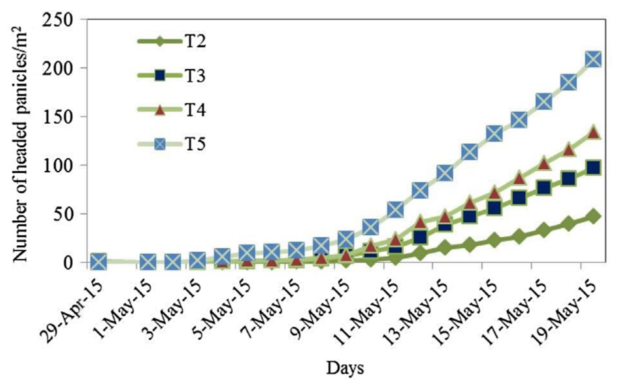


**Figure 5.** Effects of water treatment on daily headed panicle.

**Table 4.** Effect of water treatment on panicle number, panicle weight and panicle length at harvest.

| Treatments | Average panicle number per hill | Average panicle weight (g) | Average panicle length (cm) |
|---|---|---|---|
| T5 | 16.87 | 2.04 | 24.52 |
| T4 | 15.74 | 2.01 | 25.35 |
| T3 | 16.32 | 1.91 | 24.97 |
| T2 | 15.44 | 1.71 | 24.65 |
| P | ns | ns | ns |

ns: not significantly different at $p < 0.05$ level by Turkey's test.

Water treatments affected average grain numbers per panicle, grain weight per panicle, grain filling rate, and 1000 grains weight (Table 5). The lowest values for these parameters were observed in $T_{2\ cm}$. Results were similar for average grain number per panicle between $T_{5\ cm}$ and $T_{2\ cm}$, however water stress significantly affected grain weight per panicle in $T_{2\ cm}$ and grain filling rate in $T_{2\ cm}$ and $T_{3\ cm}$. Grain weight per panicle was reduced by 32% in $T_{2\ cm}$, while unfilled grain percentage was 18.7%, 20.9%, 25.1%, 31.1% for $T_{5\ cm}$, $T_{4\ cm}$, $T_{3\ cm}$, and $T_{2\ cm}$, respectively. For 1000 grains, 17.5% of the weight was lost in $T_{2\ cm}$.

The results for biomass aboveground, grain yield, and HI illustrated in Table 6 show that grain yield was significantly reduced in $T_{2\ cm}$, while $T_{3\ cm}$ and $T_{4\ cm}$ produced comparable results to $T_{5\ cm}$. The yield loss in $T_{2\ cm}$ was 3.2 times more than $T_{3\ cm}$ and 14 times more than $T_{4\ cm,}$ whilst $T_{3\ cm}$ was

**Table 5.** Effect of water treatment on grain number per panicle, grain weight per panicle, grain filling rate and 1000-grain weight.

| Treatments | Grain number per panicle | Grain weight per panicle (g) | Grain filling rate% | 1000-grain weight (g) |
|---|---|---|---|---|
| T5 | 109.20$^{ab}$ | 1.91$^{a}$ | 81.31$^{a}$ | 15.99$^{a}$ |
| T4 | 112.83$^{a}$ | 1.99$^{a}$ | 79.15$^{a}$ | 15.70$^{a}$ |
| T3 | 110.85$^{a}$ | 1.80$^{ab}$ | 74.91$^{b}$ | 14.80$^{a}$ |
| T2 | 107.09$^{b}$ | 1.67$^{b}$ | 68.88$^{c}$ | 13.60$^{b}$ |
| P | * | * | * | * |

*Mean with columns not followed by the same letter (a,b) is significantly different at $p < 0.05$ level by Turkey's test; ns: not significantly different.

**Table 6.** Effect of water treatment on biomass aboveground, grain yield, harvest index, yield losses and yield reduction.

| Treat-ments | Biomass aboveground (ton/ha) | Grain yield(ton/ha) | Harvest index (HI) | Yield losses (kg/ha) | Yield reduc-tion % |
|---|---|---|---|---|---|
| T5 | 12.09$^{a}$ | 5.74$^{a}$ | 0.48$^{a}$ | | |
| T4 | 11.77$^{ab}$ | 5.65$^{a}$ | 0.48$^{a}$ | 90 | 1.57 |
| T3 | 11.71$^{b}$ | 5.35$^{a}$ | 0.46$^{a}$ | 390 | 6.79 |
| T2 | 10.98$^{c}$ | 4.48$^{b}$ | 0.41$^{b}$ | 1260 | 21.95 |
| P | * | * | * | – | – |

*Mean with columns not followed by the same letter (a,b,c) is significantly different at $p < 0.05$ level by Turkey's test.

4.3 times more than $T_{4\ cm}$. The lowest yield reduction was observed in $T_{4\ cm}$ at 1.57%.

### *Water use efficiency*

Rainfall, irrigation, and water use efficiency is highlighted in Table 7. Cumulative rainfall recorded from transplanting to harvest represented 35, 43, 58, and 87% of the gross irrigation water applied in $T_{5\ cm}$, $T_{4\ cm}$ $T_{3\ cm}$, and $T_{2\ cm}$, respectively. The highest rainwater productivity was achieved in $T_{5\ cm}$ (2.07 kg/m$^3$), and then gradually decreased to $T_{2\ cm}$ (1.62 kg/m$^3$). The highest TWP, 0.75 kg/m$^3$ and IWP 1.40 kg/m$^3$ were observed in $T_{2\ cm}$. The lowest grain production loss (0.06 kg) was observed in $T_{4\ cm}$, indicating that 0.06 kg of grain was lost for saving 1 m$^3$ of water.

## Discussion

In AWD irrigation, paddy fields are under periodic irrigation and drought and are closely related to both external factors (rainfall, air temperature, etc.) and internal factors (soil type and properties, plant status, etc.) (Bouman, 2007; Shao et al., 2014). In this research, irrigation was applied every 7 days, and the soil water trend was analyzed according to the soil water content at 15 and 25 cm depth and the number of days it settled below the stress threshold. The critical line in this study was the stress threshold level which indicated that $T_{2\ cm}$ was mostly affected during the time of high water demand (panicle initiation) compared to the other treatments. Rice sensitivity to water stress was observed in plant height reduction at panicle initiation ($T_{2\ cm}$ and $T_{3\ cm}$) and heading stage ($T_{2\ cm}$) as drought stress tend to induce a decline in net photosynthesis and reduced growth rate through inhibition of cell elongation or cell division. Under water stress, plants reduced evapotranspiration which leads to decrease in photosynthesis and in turn induced the decrease in chlorophyll, height, and tiller number (Kima et al., 2014; Mostajean & Eichi, 2009). It is well known that water restriction may retard plant growth and reduce plant height, however, as demonstrated by $T_{3\ cm}$, plants subjected to slight water stress conditions during panicle initiation recovered faster under well-watered conditions. Water stress in $T_{3\ cm}$ was not as severe as $T_{2\ cm}$, and hence plant height recovery was faster, yielding comparable height to $T_{5\ cm}$ and $T_{4\ cm}$ at heading. Kima et al. (2014) confirmed that plants recovered from the effects of water stress that occurred during vegetative stage and performed similar to the highest water treatment at heading stage however, the extent of recovery due to re-watering strongly depends on pre-drought intensity and duration (Xu et al., 2010). On the contrary, tillering was not significantly affected by water treatments, this is supported by Nguyen et al. (2009) who compared various water saving systems in rice and found no significant difference in tiller number among treatments and suggested that tillering was less sensitive than other characteristics such as plant height and leaf area. Akram et al. (2013) also noted that tillers number per hill of different rice cultivars were not significantly affected by soil moisture stress in all growth stages. Significant differences were observed among water treatments for LAI indicating that leaf area development is sensitive to water stress. Davantgar et al. (2009) explained that leaf area development is more delicate to water deficits due to the inhibition of leaf cell expansion or division by water stress, which accordingly is the consequence of the critical role for the turgor in leaf cell expansion process. Absence of turgor in leaf cells significantly attributes to reduction in LAI by the effects

**Table 7.** Effect of treatments on water use efficiency.

| Treatments | Rain (m$^3$/ha) | Irrigation (m$^3$/ha) | TWP (kg/m$^3$) | RWP (kg/m$^3$) | IWP (kg/m$^3$) | Water Savings (m$^3$/ha) | Irrigation water savings (%) | Water saving impact (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| T5 | 2768 | 8000 | 0.53 | 2.07 | 0.72 | | | |
| T4 | 2768 | 6400 | 0.62 | 2.04 | 0.88 | 1600 | 20 | 0.06 |
| T3 | 2768 | 4800 | 0.71 | 1.93 | 1.11 | 3200 | 40 | 0.12 |
| T2 | 2768 | 3200 | 0.75 | 1.62 | 1.40 | 4800 | 60 | 0.26 |

of translocation via altered source–sink relationships for assimilation. In addition, the extent of greater root volume and root mass may have also contributed to greater LAI among higher water treatment as extensive root systems contribute to nutrient uptake, resulting in greater leaf elongation rates, which contributes to larger leaf size. Mishra et al. (2006) and Zhang et al. (2009) explained that high-root metabolic activity supports a high photosynthetic rate while supplying sufficient amount of nutrients to the shoot/leaf.

Root depths were unaffected by water treatments and showed comparable results. Even though water stress occurred in $T_{2\,cm}$, $T_{3\,cm}$, and $T_{4\,cm}$, it was not critical, furthermore the amount of water added through irrigation probably led to an infiltration rate that coincided in time with water uptake, and hence the availability of soil water did not reach a critical point for crop to develop deeper root system as an adaptation measure. Ascha et al. (2005) highlighted that plant become adapted to water deficiency through the possession of a pronounced root system, which maximizes water capture and allows access to water depth. Similarly, Kima et al. (2014) evaluated rice plants grown in various level of soil saturation and observed that plants grown in low soil water saturation showed no significant difference in root length and root dry weight when compared to plants grown in high soil water saturation and concluded that such results may be explained by the effects of hydraulic head pressure, which may also affect infiltration rate. Root dry biomass, root volume, and root dry weight were similar in $T_{3\,cm}$, $T_{4\,cm}$, and $T_{5\,cm}$ which may be attributed to soil water availability. Dry mass accumulation is one of the main growth factors of rice and large root dry weight matter with high root activity implies strong water and nutrient absorption capacity, which tends to favor high grain production (Kato & Okami, 2010; Mishra & Salokhe, 2010). Further observation revealed that roots were thicker and fuller in 0–10 cm soil in $T_{5\,cm}$ when compared to the other water treatments; however healthy roots were observed in all treatments. Root health may be attributed to repeated wetting and drying practiced under AWD. Zhang et al. (2009) demonstrated that a moderate AWD could enhance root growth, facilitate the remobilization of carbon reserve to grains, accelerate grain filling, and improve grain yield. Also, Thakur et al. (2011) explained that soil aerating practice not only induces greater root growth, but also enhances root activity, while Kassam et al. (2011) reported less numerous and less diverse soil biota under anaerobic soil conditions contrary to greater populations of beneficial soil biota seen under aerobic soil management. Aerobic conditions are healthy for increased soil microbial activities, which further induce an increased breakdown and subsequent release of nutrients available for plant uptake within the rhyzosphere._ENREF_27 Ndiiri et al. (2012) expressed that repeated wetting and drying process in system of rice intensification practices contribute high nitrogen availability and high-nitrogen usage efficiency.

The exposure of crop to temporary water stress during the drying cycles under AWD affected leaf chlorophyll content and RWC in $T_{2\,cm}$ and $T_{3\,cm}$ at panicle initiation. Leaf greenness is an indicator of plant health which may be affected by both nitrogen leaf content and water stress. Cha-Um et al. (2010) evaluated water deficit stress in four *indica* rice genotype and concluded that RWC in the flag leaf was positively correlated with total chlorophyll, and total chlorophyll and total carotenoids in all rice cultivars were drastically degraded when subjected to severe water stress. Furthermore, water stress at panicle initiation ($T_{2\,cm}$ and $T_{3\,cm}$) may have also affected the biochemical processes during plants development. This is supported by Akram et al. (2013) who clarified that water stress at panicle initiation caused a disturbance in the biochemical and physiological processes and adverse effect of enzymatic activities which drastically reduced physiological parameters such as stomatal conductance and chlorophyll pigments leading to severe decrease in photosynthetic rate, transpiration rate, and RWC. Zhang et al. (2010) also highlighted that under alternate wetting and severe soil drying (WSD) regime, cytokinin levels were reduced when compared to conventional irrigation and alternate wetting and moderate soil drying (WMS) and explained that changes of hormone in the leaves under different treatments were closely associated with those of the photosynthetic rate noting a high correlation between hormone content and leaf photosynthetic rate. While Akram et al. (2013) and Lafitte (2002) explained that reduction of leaf RWC was progressively related to soil water content especially in water deficit stress cultivars.

Water restriction affected the number of reproductive tillers in $T_{2\,cm}$ causing a significant decline in headed panicle per $m^2$ decreasing it by 443% compared to $T_{5\,cm}$. By delaying plant growth, water stress during panicle initiation delayed the heading rate which decreased panicle number per hill. Observation by Akram et al. (2013) indicated soil water stress at panicle initiation was more destructive to panicle number per hill, panicle length, panicle dry weight, shoot dry weight, and total grains per panicle, irrespective of the cultivars resulting in drastic decrease per hectare in paddy yield. In this research however, average panicle number per hill, average panicle length and average panicle weight yielded similar results but decreased with the lowest water treatment. The effect of assimilates being translocated from plant parts at panicle initiation may be one of the reasons for the yielding of comparative results. Davantgar et al. (2009) explained that mild water stress at mid-tillering affects assimilates translocation from most plant parts to the panicles via altering source–sinks relationships. The reduction in leaf cell expansion decreased sink strength for vegetative growth and lessened the competition with panicle growth assimilates. From heading to harvest, a total of 2768 $m^3$/ha of rainfall was registered and may have also contributed towards overcoming the effects of water stress that occurred during early panicle initiation in some treatments. Jones (2004) emphasized that the response of different plants to water stress is very complex and various mechanism are adopted by plants when they encounter drought stress at various growth stages. Since there was a delay in heading, and panicle initiation occurred at the same time with flowering, water stress greatly affected the flowering stage which also affected average grain number per panicle, grain weight per panicle, grain filling rate, and 1000 grain weight. Similar observation was made by Davantgar et al. (2009) and Sarvestani et al. (2008) who explained that water stress decreased yield and increased the delay of flowering at mid-tillering, vegetative, and booting stages compared to well-watered plants. Likewise, Zhang et al. (2010), Cabangon et al. (2011), and (Yang et al., 2007) scheduled irrigation based on soil moisture and found significant difference within treatment, explaining that compared with conventional flooding, the percent of filled grains, grain weight, and grain yield in alternate WMS were significantly increased but were markedly reduced in the alternate WSD condition. This is likely because water stress slows down carbohydrate synthesis and/or weakened the sink strength at reproductive stages and aborts fertilized ovaries (Rahman et al., 2002). Kumar et al. (2006) showed that percentage of unfilled grains were significantly higher in sites that were affected by drought at the reproductive stage moreover, Davantgar et al. (2009) observed that water stress at flowering causes flower abortion, grain abscission, and increase in unfilled grain percentage. As a result, this may have induced spikelet sterility or grain filling delay leading to high unfilled grain percentage which further reduced overall grain yield in $T_{2\,cm}$. Several research on AWD irrigation, proved an increased in grain yield (Mishra & Salokhe, 2010; Nyamai et al., 2012; Yao et al., 2012; Zhang et al., 2008; Zhang et al., 2009), but also reduced in others (Belder et al., 2004; Chapagain & Riseman, 2011; Tabbal et al., 2002) when compared to continuous submergence. The discrepancies among studies may be attributed to variations in soil hydrological conditions and the timing of irrigation methods (Belder et al., 2004; Yao et al., 2012). Moreover, the yield of any crop is dependent on the combination of genetic makeup, physiological process, and agronomic attributes, and any degree of imbalance in the said parameters may hamper the crop yield (Akram et al., 2013).

Overall, the highest rainwater productivity was produced by $T_{5\,cm}$ (2.07 kg/$m^3$), whereas the highest TWP (0.75 kg/$m^3$) and IWP 1.40 kg/$m^3$ was produced by $T_{2\,cm}$. However, the lowest yield reduction (1.57%) and grain production loss (0.06 kg) was achieved in $T_{4\,cm}$, indicating that 0.06 kg of grain was lost for saving 1 $m^3$ of water. Zhang et al. (2010) compared different water regime and expressed that grain yield and water use efficiency were significantly increased when soil water potential was reduced to 25 kPa in AWD. Indicating that drying condition in AWD is the most important factor affecting grain yield, and soil drying to 25 kPa is beneficial to grain growth during grain filling. Therefore, based on the soil stress threshold level and the number of days the water settled below the stress threshold, the weekly application of 4 cm ponded water depth led to the lowest yield reduction (1.57%), grain production loss (0.06 kg), optimal water productivity, and water saving of 20%, and appeared suitable and beneficial to rice crop.

## Conclusion

The weekly application of 2 cm ($T_{2\,cm}$) ponded water depths revealed that plants were more vulnerable to water stress especially at the panicle initiation stage. Water stress led to a reduction in plant height, headed panicles, grain filling rate, 1000 grain weight, and overall yield compared to the other water treatments. $T_{3\,cm}$ and $T_{4\,cm}$ experienced minor water stress and were able to yield comparable to $T_{5\,cm}$. The 4 cm ($T_{4\,cm}$) ponded water depth from transplanting to heading produced the lowest yield reduction and grain production loss, with no significant reduction in yield compared to $T_{5\,cm}$; therefore, $T_{4\,cm}$ remains suitable for reducing rice irrigation water use and matching the required crop water. The application of 5 cm ($T_{5\,cm}$) ponded water depth from transplanting to heading increased the rainwater productivity but induced low IWP. Since rainwater is free of cost, high amount of irrigation water during the dry season appeared costly and non-beneficial. Moreover, it has demonstrated that high or acceptable rice yields can be achieved under non-flooding conditions with safe AWD practice. AWD is only one of several techniques which offer opportunities to increase rice production using less water. Weekly application of 4 cm ponded water depth can be recommended to farmers as an alternative to save irrigation water. In this context, combining irrigation and maximizing the use of rainfall effectively enhanced AWD in this particular area and such results may be replicated in locations with similar environmental conditions.

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## Disclosure statement

No potential conflict of interest is reported by the authors.

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