Maximizing Rainfall in Lowland Paddy Rice through Water Depths Control and Alternate Wetting and Drying Irrigation Technique in Southern Taiwan

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Abstract: Rainfall along with the use of alternate wetting and drying irrigation technique is proposed to minimize water use and optimize crop yield and water productivity in paddy rice cultivation. A field experiment was conducted to determine the most suitable ponded water depth for reducing paddy rice irrigation. Water treatments of $T2_{cm}$, $T3_{cm}$, $T4_{cm}$, and $T5_{cm}$ were applied weekly from transplanting to early heading through a complete randomized block design with four replications. The results showed that yield loss in $T2_{cm}$ was 3.5 times more than that of $T3_{cm}$ and 14 times more than $T4_{cm}$. The highest irrigation water productivity and total water productivity was produced in $T2_{cm}$, whereas rainwater productivity was greater in $T5_{cm}$. The weekly application of $T4_{cm}$ ponded water depth along with rainfall matched the required crop water and produced the lowest yield reduction and grain production loss, in addition to 20% water saving. Water stress at panicle initiation decreased the daily headed panicle per square meter by 155%, 214%, and 443% in $T4_{cm}$, $T3_{cm}$, and $T2_{cm}$ compared to $T5_{cm}$. However, the decrease of this parameter was followed by total recovery caused by the effective rainfall contribution.

1. Introduction

Global agriculture in the 21st century faces the tremendous challenge of providing enough food for a growing population under increasing scarcity of water resources, while minimizing environmental consequences [1,2]. Fresh water for irrigation is becoming increasingly scarce because of population growth, increasing urban and industrial development, and the decreasing availability resulting from pollution and resource depletion [1,3]. The world food security remains largely dependent on irrigated lowland rice which is the main source of rice supply [4]. It provides 75% of the total rice production [1], and consumes more than 50% of total fresh water. By 2025, it is predicted that 15–20 million hectares of irrigated rice field may suffer from physical water scarcity, and the world's farmers should be producing about 60% more rice than at present to meet the food demand of the expected world population [5]. The challenge for sustainable rice production is to decrease the amount of water while maintaining or increasing grain yields [6].

Since the foreseen increase in the supply of rice is constrained by lack of sufficient available water, the most appropriate solution for worldwide water shortage is to make efficient use of agricultural water [7]. China has pioneered various water-saving irrigation technologies to achieve more water-efficient irrigation for agricultural systems [8,9]. Among the various water saving methods, the most widely promoted one for rice is alternate wetting and drying (AWD) irrigation [10,11]. It is reported that AWD practices could reduce both water use and greenhouse gas (GHG) emissions without seriously sacrificing grain yield in rice systems [2]. 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 re-irrigating (to achieve flooded conditions) after a fixed number of non-flooded days, when a certain threshold of soil water potential is reached, when the ponded water table level drops to a certain level below the soil surface, when cracks appear on the soil surface, or when plants show visual symptoms of water shortage [8]. Commonly, irrigation is applied to obtain 2–5 cm ponded water depth after a certain number of days (ranging from two to seven) have passed following the disappearance of ponded water [5]. Yield penalty was commonly observed under AWD compared with continuously flooded (CF)-irrigated rice [12]. Generally, however, AWD increased water productivity with respect to total water input because the yield reduction was smaller than the amount of water saved [13]. Tuong et al. [5] assessed the efficiency of AWD compared with CF and found that AWD yielded better than CF in terms of water savings and farm profitability. However, rice is very sensitive to water stress and attempts to reduce water may result in yield reduction and threaten food security. Therefore, efficient irrigation water use requires effective water management during the entirety of the crop production cycle.

Rice is also 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 TND (Taiwan New Dollar) 41.48 billion (about USD 1.37 billion) in 2014 [14]. There are two cropping seasons for paddy rice in Taiwan. The first crop is cultivated in February and harvested in July, and the second crop is cultivated in August and harvested in December [15]. Taiwan is located in a rainy region with 78% of the rainfall occurring from May to October, with possibilities of rainfall reaching up to 90% in the southern region. Taiwan has an annual average precipitation of 2500 mm, which is higher than the world's average of 834 mm; however, there is still grave water demand, and fresh water for irrigation limits rice production. Apart from rapid urbanization, industrialization, and high irrigation water consumption from the agriculture sector (80%), 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 [16,17], furthermore, this situation is exacerbated by climate change. In 2014, rice production was compromised as a consequence of extended drought forcing the Ministry of Economic Affairs (MOEA) to implement water rationing measures by fallowing approximately 5% of Taiwan's cultivated land [14].

Agriculture water resource scarcity directly affects crop productivity and aggravates food deficit problems for millions of people [18]. In this regard, the maximization of water resources is imperative and the combined effects of rainfall and irrigation management should be addressed together regarding the environment specificities for maximizing water use efficiency and yield per unit of irrigation water applied. Thus, AWD can be optimized and may reduce irrigation cost, 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 are to apply AWD irrigation to determine the most effective ponded water depth leading to optimum water uptake and low yield losses, while simultaneously maximizing rainfall use alongside scheduled irrigation, and to determine the morphological changes in paddy rice caused by the ponded water treatments. It is expected that the AWD technique can be optimized, through strategic irrigation management while taking full advantage of rainfall occurrences. Such an approach is less documented in areas such as southern Taiwan, hence the reason for the current field experiment.

2. Materials and Methods

2.1. Experimental Site and Trial Design

The experiment was conducted from February to June 2015 in the irrigation experimental field of National Pingtung University of Science and Technology in southern Taiwan, located at 22.39° (N) latitude and 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 kept constant at 5 cm, 4 cm, 3 cm, and 2 cm representing $T5_{cm}$, $T4_{cm}$, $T3_{cm}$, and $T2_{cm}$.

2.2. Crop Management and Irrigation Management

Twenty-five day old seedlings were obtained from a seed nursery and were manually transplanted on 1 February 2015. 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 by frequent manual weeding. Irrigation treatments were applied immediately after transplanting and the irrigation interval was scheduled at seven days. Equation (1) was used to obtain the desired water volume at required depth considering seepage and infiltration in the experimental design and results.

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

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 2015. Thereafter, the rain was frequent and the crop was subjected to rainy conditions.

2.3. Soil Water Content and Soil Trend Analysis

The soil water content was monitored every two days from one month after transplanting to three weeks before harvest using the gravimetric method. Soil samples were collected using an auger in three different locations within each plot at 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 (4).

$$SW = \frac{100 \times (fresh\ weight - dry\ weight)}{dry\ weight} \times \gamma s \tag{2}$$

where SW is the soil water content and γs 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) [19].

$$SW_{Sat} = 1000\ (Sat) \times Z_r \tag{3}$$

$$SW_{FC} = 1000\ (FC) \times Z_r \tag{4}$$

$$SW_{WP} = 1000\ (WP) \times Z_r \tag{5}$$

$$SW_{ST} = 1000\ (1 - P)Sat \times Z_r \tag{6}$$

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 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 represents 20% of the saturation for rice crop; Z_r is the sample collection depth (m).

2.4. 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. Five 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 [20]. A uniform soil volume of 1570 cm^3 was excavated to collect root samples for all treatments. Roots were carefully washed and removed from uprooted plants. Root volume was measured by the water displacement method of putting all the roots in a measuring cylinder and getting the displaced water volume [21]. Root depth was obtained by direct manual measurements of the 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.

2.5. Leaf Chlorophyll Content and Relative Water Content

A chlorophyll meter (model SPAD-502, MINOLTA, Osaka, 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 [22,23]. 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 of chlorophyll content among treatments with three observations made per leaf. Analysis of leaves sampling patterns done by Chapman and Bareto [24] 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 relative water content (RWC) was calculated from fresh weight (FW), dry weight (DW), and turgid weight (TW) [25].

$$\text{RWC}\ (\%) = [(\text{FW} - \text{DW})/(\text{TW} - \text{DW})] \times 100 \tag{7}$$

2.6. Measuring of Yield and Yield Components

To analyze the heading rate, daily headed panicle numbers was determined in each plot from the appearance of the first panicle until 50% of the farm headed. 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 [4]. 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 were randomly picked 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, excluding those in edges, for grain yield per unit of area (tha^{-1}) determination. Three samples of harvested grains were randomly picked from each replicate and the dry weight was determined. Grain weight per panicle, and grain yield for unit area 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 grain production of each plot and weighed for the 1000 grain 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, using mass as the basis, as the ratio of filled grain weight out of the total grain 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 out of the total straw yield.

2.7. Water Productivity Assessment

The total water productivity (TWP), irrigation water productivity (IWP) and rain water productivity (RWP) were calculated according to Equations (8)–(10) [26]:

$$\text{TWP} = \frac{\text{Y}}{\text{TWU}} \tag{8}$$

$$\text{IWP} = \frac{\text{Y}}{\text{IWU}} \tag{9}$$

$$\text{RWP} = \frac{\text{Y}}{\text{RWU}} \tag{10}$$

where TWP, IWP, and RWP are the total water (rain + irrigation), irrigation water, and rain water productivity, respectively, expressed in $\text{kg}\cdot\text{m}^{-3}$; Y is the grain yield ($\text{kg}\cdot\text{ha}^{-1}$), TWU, IWU, and RWU are the total water, irrigation water, and rain water used, respectively, expressed in $\text{m}^3\cdot\text{ha}^{-1}$.

Grain production losses were calculated considering the yield in the highest water treatment (T5_{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).

2.8. Data Analysis

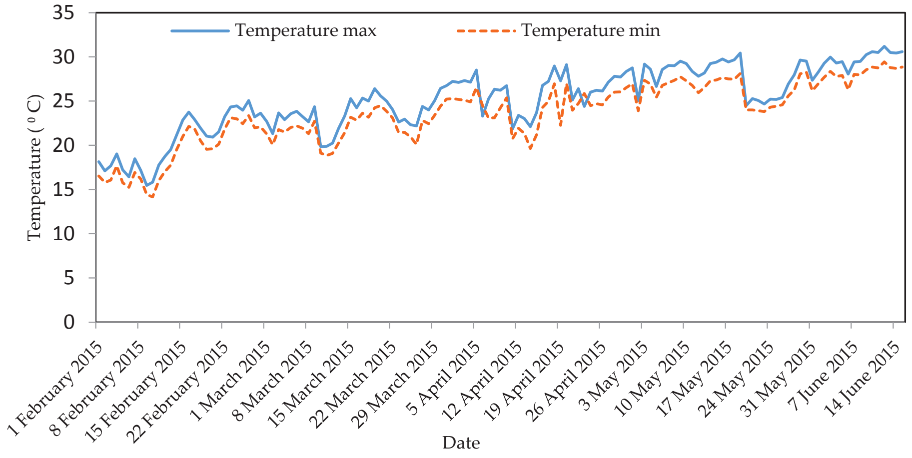
The statistical analysis applied on the data includes correlation, and the analysis of variance was done using SPSS 18 software (*PASW Statistics for Windows*, version 18.0.; SPSS Inc.: Chicago, IL, USA, 2009). The significance of the treatment effect was determined using F-test and means were separated through Turkey's test at a 0.05 significance level.

3. Results and Discussion

3.1. Agro-Hydrological Conditions during the Growing Season

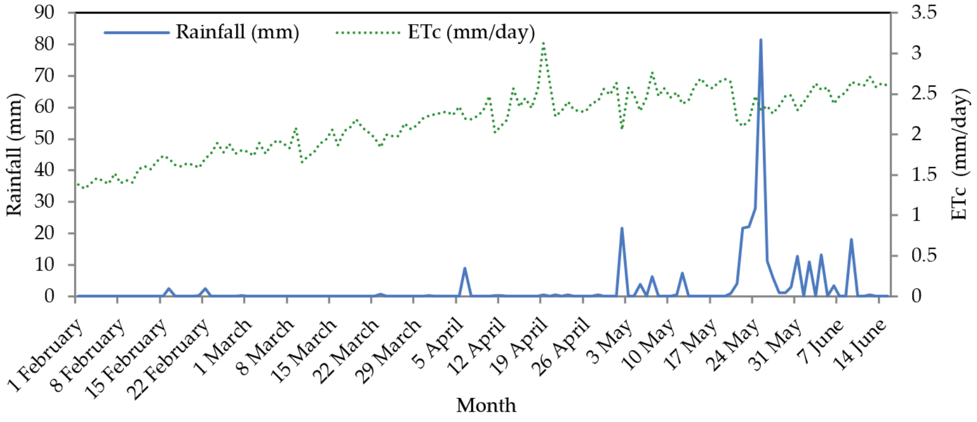
The daily maximum temperatures, minimum temperatures, daily rain fall, and crop evapotranspiration (ETc) during the crop production cycle are presented in Figure 1. The weather data were recorded at the National Pingtung University of Science and Technology Agro-Meteorological station. Maximum and minimum temperatures (see Figure 1a) varied from 16.4 to 31.1 °C with a mean value of 25.1 °C, and from 14.1 to 28.8 °C with a mean value of 23.5 °C, respectively. The low values for these two parameters were observed in February while the high values were observed in June. February was recorded as the driest month during the crop cycle.

Daily rainfall (see Figure 1b) ranged from 0 to 81.3 mm with monthly recorded values (February, March, April, May, and June 2015) of 5.2, 0.9, 11.2, 229.2, and 30.1 mm, respectively. Rainfall was more frequent during the month of May compared to other months and coincided with the final stages of panicle initiation and throughout heading. The ETc was obtained by multiplying the reference crop evapotranspiration (ETo) per adjusted crop coefficient (Kc) [14]. Crop evapotranspiration varied along the production cycle and ranged from 1.33 to 3.12 mm/day with the lowest observed value in February (vegetative stage) and the highest value observed in April (panicle initiation). From panicle initiation up to the onset of harvest the crop water demand was above 2 mm/day.



(a)

Figure 1. *Cont.*



(b)

Figure 1. (**a**) Daily maximum and minimum temperatures; (**b**) Daily rainfall and crop evapotranspiration during the crop production cycle.

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–12 May 2015), and 2197 m^3/ha from heading (12 May 2015) to harvest (16 June 2015). During the vegetative stage rainfall represented 3.87%, 2.58% 1.93%, and 1.55% of irrigation water applied in treatments $T2_{cm}$, $T3_{cm}$, $T4_{cm}$, and $T5_{cm}$, 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 production cycle occurred from heading to harvest.

3.2. Soil Water Content of Different Water Treatments

The soil water trend analysis was based on the soil stress threshold and was recorded from the vegetative to heading stage during the crop production cycle (see Figure 2). Throughout the vegetative stage, the soil water content reached its maximum every two days after irrigation and then a sharp decline occurred until the next irrigation. The highest water treatment ($T5_{cm}$) produced the highest soil water content throughout the crop production cycle. Soil water content 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. The soil water content for $T2_{cm}$ produced the lowest values throughout the growing cycle, but was never below the soil stress threshold during the vegetative stage, whereas that of $T4_{cm}$ and $T3_{cm}$ was frequently between highest and lowest water treatments at this time. At panicle initiation, the soil water content for $T2_{cm}$ fell below the soil stress threshold level six times, with 79.4 mm recorded as the lowest value. Soil water content for $T3_{cm}$ fell below the soil stress threshold level once (84.8 mm), however, low values of 87.3, 86.3, and 87.5 mm were also recorded. From 18 May 2015 onwards, rainfall was frequent and irrigation was suspended. The soil water content at this time was closer to saturation levels in all treatments. Previous studies [27,28] have confirmed that the critical stages for rice sensitivity to water stress are during panicle initiation, anthesis, and grain filling. Boonjung and Fukai [29] highlighted that plants which suffer mild stress during early panicle development stage suffered yield reduction of around 30% due to reduction in the number of spikelets per panicle. Water stress was observed during the high crop water requirement period (panicle initiation), with $T2_{cm}$ being significantly affected compared to the other treatments.

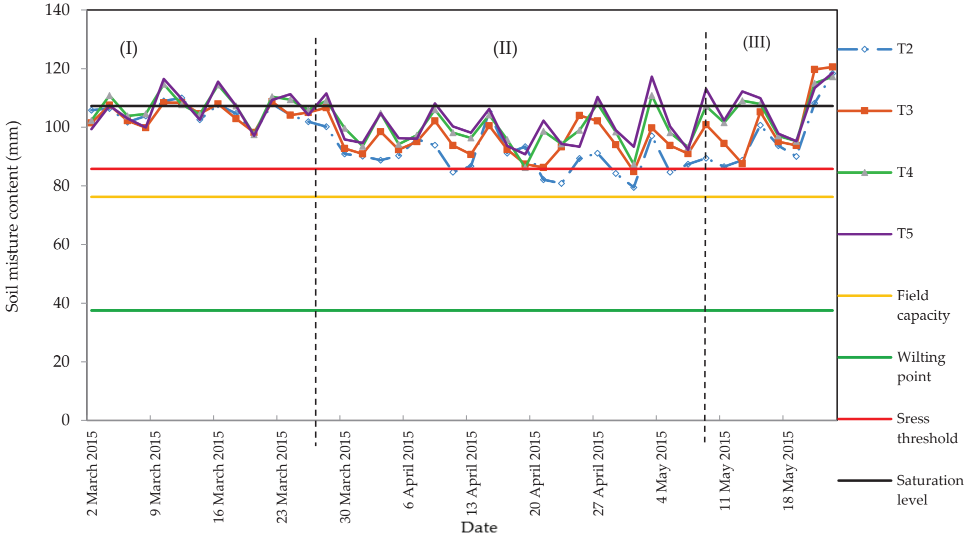


Figure 2. Soil water content at (I) vegetative, (II) panicle initiation, and (III) early heading stage.

3.3. Crop Growth

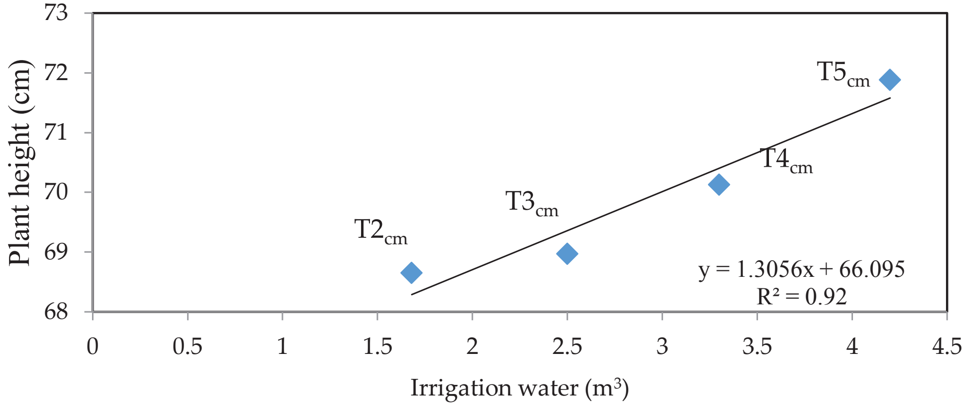
Growth parameters of plant height and tiller numbers presented in Table 1 show that plant height was significantly affected by water treatments at panicle initiation and heading stage. Under water stress, plants reduced evapotranspiration which led to decreases in photosynthesis which in turn induced the decrease of chlorophyll, height, and tiller number [13]. Reddy et al. [30] concluded that drought stress induced a decline in net photosynthesis and reduced growth rate. Low plant heights were notable in lower water treatments, with $T2_{cm}$ and $T3_{cm}$ showing significant height differences compared to $T5_{cm}$ at the panicle initiation. At heading, the lowest plant height was recorded in $T2_{cm}$, while comparable height was seen among $T5_{cm}$, $T4_{cm}$, and $T3_{cm}$. Water stress in $T3_{cm}$ was not as severe as that of $T2_{cm}$, hence the reason $T3_{cm}$ was able to produce comparable height to $T5_{cm}$ at heading. Water restrictions at panicle initiation decreased average plant height by 8.35%, 4.21%, and 2.50%, while at heading height was reduced by 4%, 2.9%, and 2.2% in $T2_{cm}$, $T3_{cm}$, and $T4_{cm}$, respectively. A high correlation ($R^2 = 0.92$ and $R^2 = 0.93$, respectively) was found between plant height and irrigation water application during panicle initiation and heading (see Figure 3a,b). It is well known that water restriction may retard plant growth and reduce plant height, however, plants subjected to slight water stress conditions during the panicle initiation stage recovered faster under well water conditions. Lilley and Fukai [31] demonstrated that severe water deficit suspended apical development until re-watering occurred, while mild water deficit reduced the rate of apical development. Kima et al. [32] confirmed that plants recovered from the effects of water stress that occurred during vegetative stage and performed as well as the highest water treatment at heading stage. The extent of recovery due to re-watering strongly depends on pre-drought intensity and duration [33].

No significant differences were observed for tiller numbers among water treatments, however, the smallest tillers and the lowest tiller numbers were observed in $T2_{cm}$. Nguyen et al. [34], in comparing various water saving systems in rice, found no significant difference in tiller number among water treatments and suggested that tillering was less sensitive than other characteristics, such as plant height and leaf area. Akram et al. [35] also noted that in all growth stages, tiller number per hill of different rice cultivars was not significantly affected by soil moisture stress. Results show correlation ($R^2 = 0.78$) at panicle initiation and ($R^2 = 0.82$) at heading, thereby revealing significant correlations between irrigation water and tiller number (see Figure 3c,d).

Table 1. Effects of water treatments on plant height and tiller numbers.

	Panicle Initiation		**Heading**	
Treatments	**Plant Height**	**Tiller Numbers**	**Plant Height (cm)**	**Tiller Numbers**
T5	71.88 ^{a*}	14.64	86.68 ^{a}	19.72
T4	70.12 ^{ab}	13.93	84.77 ^{ab}	19.82
T3	68.97 ^{b}	14.16	84.17 ^{ab}	19.32
T2	68.65 ^{b}	13.28	83.32 ^{b}	18.75
P	*	ns	*	ns

* = mean with columns not followed by the same letter indicate a significant difference at the $p < 0.05$ level as determined by Tukey’s test; ns = not significantly different.



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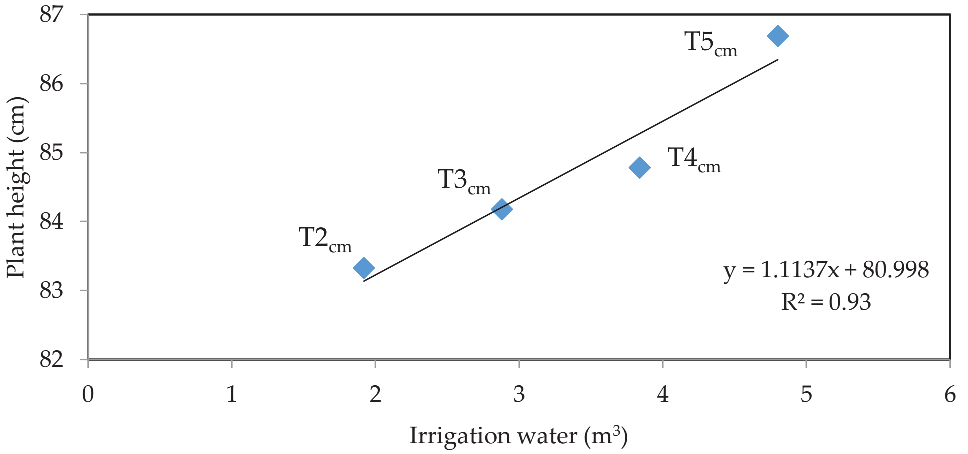
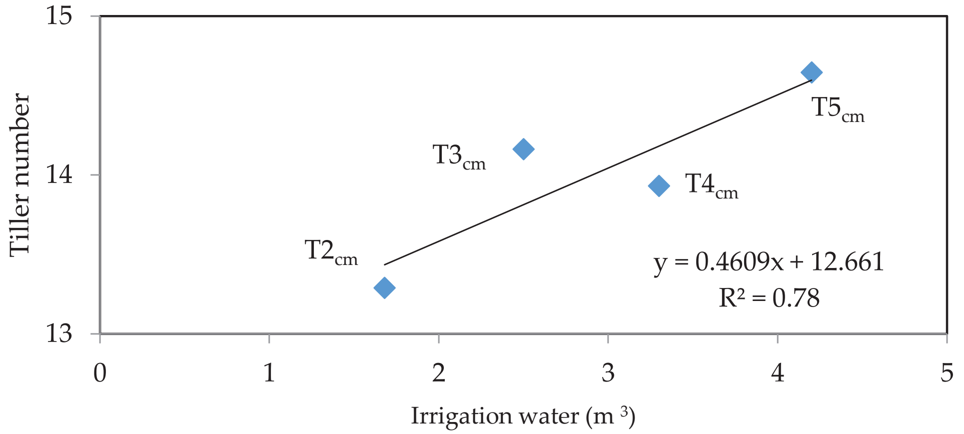


(b)

Figure 3. *Cont*.



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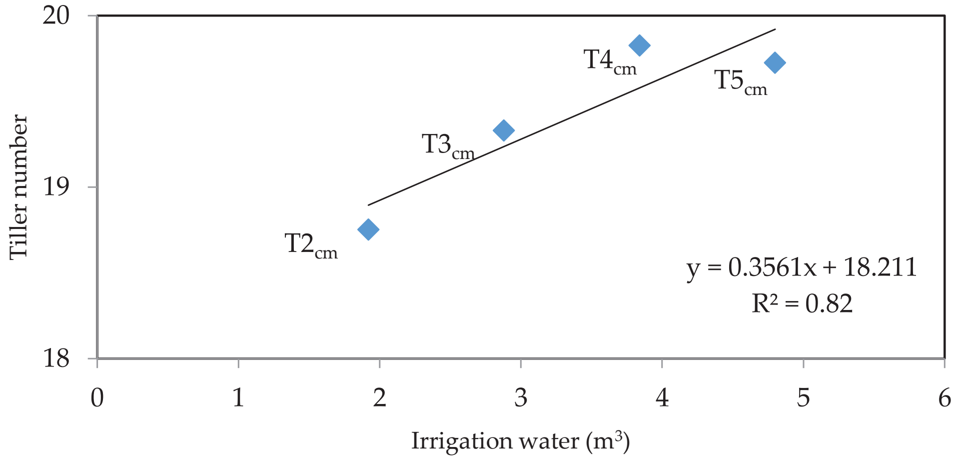

(d)

Figure 3. Relationship between plant height and irrigation water at panicle initiation (**a**) and heading (**b**) and between tiller numbers and irrigation water at panicle initiation (**c**) and heading (**d**).

3.4. Dry Biomass, Root Dry Weight, Root Depth, and Root Volume

The results of root parameters and dry biomass are presented in Table 2. The highest values for dry biomass, root volume, and root dry weight was produced in $T5_{cm}$. No significant differences were observed between dry biomass and root volume for $T3_{cm}$ and $T4_{cm}$, however, significant differences were observed between

$T5_{cm}$ and $T2_{cm}$. Blackwell et al. and Turner et al. [36,37] observed that biomass production decreases with decreasing water availability. In addition, dry biomass accumulation is one of the main growth factors of rice and large root dry weight matter as high root activity implies strong water and nutrient absorption capacity, which tend to favor high grain production [38,39]. Lilley and Fukai [31] explained that rice cultivars differ in physiological response to water deficit that is associated with differences in water extraction capability. Furthermore, the response of different plants to water stress is much more complex, and various mechanisms are adopted by plants when they encounter drought stress at various growth stages [40]. The results also indicate that no significant differences were observed for root depths for all treatment. Ascha et al. [41] highlighted that plants become adapted to water deficiency through the possession of a pronounced root system, which maximizes water capture and allows access to water depth. Kima et al. [32] evaluated various water treatments for water use efficiency under saturated soil culture and noted that lower root depth and root weight values were produced in higher water treatments. They concluded that such results may be explained by the effects of hydraulic head pressure, which may affect infiltration rate. Further explanation revealed that, in higher water treatments, water depth on the soil surface may lead to an infiltration rate that matches in time with water uptake, and hence the availability of soil water may not reach a critical point for the crop to develop a deeper root system as an adaptation measure [32]. Root dry weight and root volume were significantly higher for $T5_{cm}$ when compared to $T2_{cm}$, but no significant differences were found among $T2_{cm}$, $T3_{cm}$, and $T4_{cm}$. Further observation showed that roots were thicker and fuller in 0–10 cm soil in $T5_{cm}$ when compared to the other water treatments. In addition, healthy roots were observed in all treatments. Root health may be attributed to repeated wetting and drying practiced under AWD. Ndiiri et al. [16] explained that of the several factors that contribute to high nitrogen availability and high nitrogen usage efficiency under system of rice intensification (SRI) management practices, the repeated wetting and drying process may have the greatest influence; moreover, lack of aeration of soil affects not only root health and functions, but also the populations of beneficial organisms that contribute to plant nutrition and health. There is also evidence that phosphorus solubilization and availability are increased by alternate wetting and drying [32].

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	27.71 ^{ab}	13.04 ^{ab}	16.89	20.30 ^{ab}
T3	28.85 ^{a}	10.94 ^{ab}	16.44	17.40 ^{ab}
T2	22.71 ^{b}	9.33 ^{b}	15.56	15.15 ^{b}
P	*	*	ns	*

* = mean with columns not followed by the same letter indicate significant difference at the $p < 0.05$ level as determined by Tukey's test; ns = not significantly different.

3.5. Leaf Chlorophyll Content and Relative Water Content

The effect of water treatments on leaf chlorophyll content and leaf relative water content (RWC) at panicle initiation is presented in Table 3. It is well established that AWD exposes crops to temporary water stress during the drying cycles and that plants adapt to water stress by stomatal closure, change in leaf turgor, and chlorophyll fluorescence. Leaf greenness is an indicator of a plant's health, and it may be affected by both leaf nitrogen content and water stress [4]. Chlorophyll content and RWC was highest in ($T5_{cm}$), with no significant differences observed among the other treatments. Cha-Um et al. [42] explained that, in evaluating water deficit stress in four *indica* rice genotypes, RWC in the flag leaf was positively correlated with total chlorophyll; moreover, total chlorophyll and total carotenoids in all rice cultivars were drastically degraded when subjected to severe water stress. However, the degradation percentage of the pigments would recover and greatly improve after re-watering. It was also noted that water use efficiency in rice subjected to water deficit declined significantly. Furthermore, Zhang et al. [43] highlighted that under an alternate wetting and severe soil drying regime (WSD), cytokinin levels were reduced when compared to conventional irrigation and alternate wetting and moderate soil drying (WMS). The explanation in support stated that changes in hormones in leaves under different treatments were closely associated with those of the photosynthetic rate, with a high correlation observed between hormone content and photosynthetic rate. There was no significant difference in chlorophyll content and RWC at the heading stage. RWC value was higher during the heading stage compared with the panicle initiation stage, since at this time the soil water content was usually higher due to frequent rain fall. Akram et al. [35] and Lafitte [44] explained that reduction of leaf RWC was related to soil water content, especially in water deficit stress cultivars.

Table 3. Chlorophyll content and leaf relative water content 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	43.92 ^{b}	62.57 ^{b}	43.43	84.90
T3	45.34 ^{ab}	65.02 ^{ab}	44.16	77.93
T2	43.61 ^{b}	60.05 ^{b}	43.72	85.15
P	*	*	ns	ns

* = mean with columns not followed by the same letter indicate significant difference at the $p < 0.05$ level as determined by Tukey's test; ns = not significantly different.

3.6. Effect of Water Treatment on Yield Components and Grain Yield

Daily headed panicle and panicle emergence were affected by water treatments (see Figure 4). Panicle numbers in $T5_{cm}$ were significantly higher, and emergence was faster compared with other treatments. When compared to $T5_{cm}$, panicle reduction rate per square meter was 155%, 214%, and 443% in, $T4_{cm}$, $T3_{cm}$, and $T2_{cm}$, respectively. The high occurrences of water stress in $T2_{cm}$ at panicle initiation caused significant declines in headed panicle per m^2, showing that water restriction affected the number of reproductive tillers. By delaying plant growth, water stress during panicle initiation delayed the heading rate, which decreased the panicle number per hill. Akram et al. [30] explained that severe soil moisture 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 a drastic decrease in per hectare paddy yield. O'Toole and Moya [45] highlighted that water deficit at any growth stage may reduce such conditions based on the magnitude of the reduction which is dependent on the severity, timing, and duration.

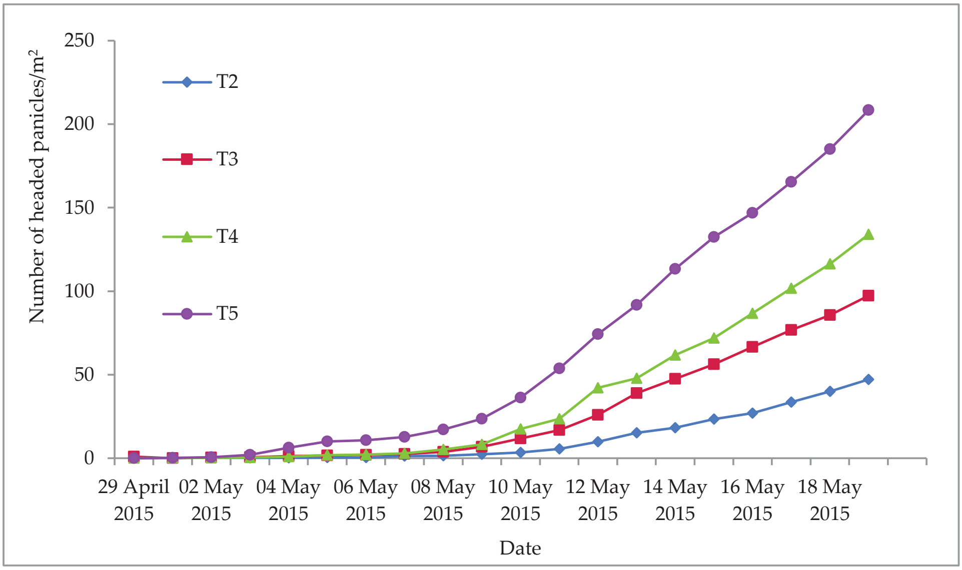

Figure 4. Effects of water treatments on daily headed panicle.

The results presented in Table 4 show that no significant differences were produced for average panicle number per hill, average panicle length, and average panicle weight; however, average panicle weight decreased with the lowest water treatment. Davatgar et al. [46] explained that mild water stress at mid tillering affects assimilates translocation from most plant parts to the panicles, via altering source sink relationships. The reduction in leaf cell expansion decreased the sink strength for vegetative growth and lessened the competition with panicle growth assimilates. Even though water stress occurred during the panicle initiation stage, it is well established that tillering and panicle initiation may occur simultaneously, and probably contributed to the translocation of assimilates during this time. The effect of assimilates being translocated from plant parts may be one of the reasons for the yielding of comparative results. From heading to harvest, a total of 2768 m^3/ha of rainfall was registered which may have also contributed towards overcoming the effects of water stress which occurred during early panicle initiation in some treatments. Kima et al. [4] explained that high rainfall occurring from heading to harvest allowed crops to overcome the effects of water stress experienced during vegetative stage, leading to recovery of yield components such as panicle number and grain number per panicle. Turner et al. [37] also suggested that the reduction of yield component by water stress is dependent on severity, timing, and duration; furthermore, previously established literature [33] has indicted that the response of different plants to water stress is much more complex and that various mechanism are adopted by plants when they encounter drought stress at various growth stages.

Table 4. Water treatments effects 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 as determined by Tukey's test.

The values in Table 5 show that water treatments significantly affected the average grain number per panicle, grain weight per panicle, grain filling rate, and 1000 grain weight. The lowest values of these parameters were observed in $T2_{cm}$. There were no significant differences observed for average grain number per panicle between $T5_{cm}$ and $T2_{cm}$, however, water stress significantly affected grain weight per panicle in $T2_{cm}$ and grain filling rate in $T2_{cm}$ and $T3_{cm}$. Grain weight per panicle was reduced by 32% in $T2_{cm}$, while unfilled grain percentage was 18.7%, 20.9%, 25.1%, and 31.1% for $T5_{cm}$, $T4_{cm}$, $T3_{cm}$, and $T2_{cm}$, respectively. For 1000 grain weight, 17.5% of the weight was lost in $T2_{cm}$. Since there was a delay in heading, and panicle initiation occurred at the same time with flowering, water stress greatly affected the flowering stage. This might be because water stress slowed down carbohydrate synthesis and/or weakened the sink strength at reproductive stages and aborted fertilized ovaries [47]. As a result, this may have induced spikelet sterility or grain filling delay, leading to high unfilled grain percentage in $T2_{cm}$.

Table 5. Water amounts effects 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 indicate significant difference at the $p < 0.05$ level as determined by Tukey's test.

The results of straw weight, grain yield, and harvest index in Table 6 show that these parameters were affected by water treatments. Grain yield in $T2_{cm}$ was significantly reduced by water stress which occurred during panicle initiation. Even though water stress occurred simultaneously in $T3_{cm}$, it was not as severe, hence $T3_{cm}$ was able to produce comparable crop yield to $T5_{cm}$ and $T4_{cm}$. The yield loss in $T2_{cm}$ was 3.5 times more than that of $T3_{cm}$ and 14 times more than that of $T4_{cm}$. The lowest yield reduction was observed in $T4_{cm}$ at 1.57%.

Table 6. Effect of water on straw weight, grain yield, harvest index, yield loss, and yield reduction.

Treatments	Straw Weight (ton/ha)	Grain Yield (ton/ha)	Harvest Index (HI)	Yield Loss (kg/ha)	Yield Reduction %
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 indicates significant difference at the $p < 0.05$ level by Tukey's test.

3.7. Water Use Efficiency

Table 7 highlights the results in terms of the amount of rainfall, irrigation, and water use efficiency. Cumulative rainfall recorded from transplanting to harvest represented 35%, 43%, 58%, and 87% of the gross irrigation water applied in $T5_{cm}$, $T4_{cm}$, $T3_{cm}$, and $T2_{cm}$, respectively. The highest rainwater productivity was achieved in $T5_{cm}$ (2.07 kg/m^3), and then gradually decreased to the lowest water treatment $T2_{cm}$ (1.62 kg/m^3). The highest total water productivity, 0.75 kg/m^3, and irrigation water productivity, 1.40 kg/m^3, were observed in the lowest water treatment T2$_{\mathrm{cm}}$. The lowest grain production loss (0.06 kg) was observed in T4$_{\mathrm{cm}}$, indicating that 0.06 kg of grain was lost for saving 1 m^3 of water. Therefore, based on lowest yield reduction (1.57%) and grain production loss (0.06 kg), the weekly application of 4 cm ponded water depth led to optimal water productivity and a water saving of 20%, and appeared suitable and beneficial for rice crops. In conducting similar research with an emphasis on saturated soil culture, Yao et al. [13] explained that 3 cm soil saturation provided the best results based on lowest yield reduction, lowest grain production loss, and water savings. However, other variables such as environmental conditions and crop variety may also determine the outcome of such results.

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

TWP = total water productivity; IWP = irrigation water productivity; RWP = rain water productivity.

4. Conclusions

The challenges to sustaining rice productivity are presently increasing, as there is greater scarcity of water and more competition for water resources. This study has shown that AWD can be optimized through efficient irrigation management and rainfall maximization, thereby concurrently achieving the dual goals of increasing grain production and reducing the water requirements for irrigated paddy rice. Rainfall induced favorable watered conditions that rose and kept the soil moisture content above the soil stress threshold during the final stages of panicle initiation and throughout the heading stage. The weekly application of T4$_{\mathrm{cm}}$ ponded water depth from transplanting to heading produced the lowest yield reduction and grain production loss while having no significant impact on yield loss compared to the highest water treatment, and is therefore suitable for increasing irrigation water productivity. On the contrary, plants exposed to T2$_{\mathrm{cm}}$ ponded water depth were more vulnerable under soil water stress and showed a reduction in yield components and overall grain yield. Likewise, the number of daily headed panicle per square meter was most affected by T2$_{\mathrm{cm}}$ (443%) when compared to T5$_{\mathrm{cm}}$. The weekly application of T5$_{\mathrm{cm}}$ ponded water depth from transplanting to heading increased the rain water productivity but induced low irrigation water productivity; on the contrary, irrigation water productivity and total water productivity was greater in

$T2_{cm}$. Since rain water use is free of cost, excess use of irrigation water during the dry season in ($T5_{cm}$) appeared costly and non-beneficial. By applying $T4_{cm}$ ponded water depth, and synchronizing the high crop water demand period with the onset of the rainy season, AWD technique efficiency can noticeably be improved. For sustainable rice production and agriculture in general, different methods and technologies for minimizing water usage are explored; however, it has been demonstrated repeatedly that high rice yields can be achieved under non-flooding conditions, and AWD is only one of several techniques which offer opportunities to raise rice production using less water. In this context, combining irrigation and maximizing rainfall can reduce rice farmers' need for irrigation water, enhance grain production, and assist in alleviating food and water shortages in rice producing countries with similar environmental conditions. Finally, water is not an easily fungible resource, and the hydrological dynamics across time and place need to be taken into account. The results presented merit further exploration taking into account additional water depths as soil hydrological condition, timing of irrigation, crop variety, and agronomic attributes may also affect crop yield.

Author Contributions: The authors are both well conversant with the content of the manuscript and have agreed to the sequence of the authorship. Victoriano Joseph Pascual conducted the field work and wrote the manuscript. Yu-Min Wang supervised the field work, and provided oversight for the analysis of data and editing of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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