

Article

# Agronomic Growth Performance of Super Rice under Water-Saving Irrigation Methods with Different Water-Controlled Thresholds in Different Growth Stages

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**Abstract:** Many water-saving techniques have been developed for rice production in response to irrigation water scarcity. The selection of the water-saving methods and the optimum thresholds for obtaining maximum benefits of these regimes are largely site-specific depending mainly on soil type, soil texture, and the environment. A two-year (2017 and 2018) experiment was conducted to evaluate the response of the agronomic growth performance, yield, and water use of super rice varieties under different irrigation regimes in Jiangsu Province, China. The irrigation regimes were comprised of different water-controlled thresholds, in different growth stages. Treatments included traditional flooding irrigation (FI, as the control) and the following four water-saving irrigation (WSI) regimes: shallow adjusting irrigation (WSI1), rainwater-catching and controlled irrigation (WSI2), controlled irrigation (WSI3), and drought planting with straw mulching (WSI4). The results showed that WSI treatments significantly increased the irrigation water use efficiency by 20.60% to 56.92% as compared with FI. The WSI treatments significantly decreased the crop evapotranspiration during the rice growth period. The grain yields of WSI1, WSI2, and WSI3 were significantly increased (6.62%~7.20% for WSI1, 8.21%~12.39% for WSI2, and 8.30%~12.91% for WSI3) as compared with that of the control, whereas WSI4 decreased the rice yield by 11.69%~18.10%. This research implies that WSI2 and WSI3 have the greatest potential for promotion in the lower reaches of the Yangtze River. An optimization of the irrigation threshold of WSI1 and WSI4 should be considered to guarantee the overall benefit.

**Keywords:** rice; agronomic growth; control thresholds; water-saving irrigation; yield

## 1. Introduction

China has the world's second largest rice planting area (18.8% of the global rice area) and the highest rice production (28.1% of the global rice production) [1–3]. Water plays an essential role in stable agricultural production, especially for paddy rice which requires more water than other staple crops such as wheat and maize [4]. However, with climate change, as well as the increasing water demand from rapid economic development and the urbanization process [1,5], increasing food production and increasing agricultural water productivity with limited water resources have become a top priority for the agricultural sector [4,6]. Consequently, several water-saving technologies have been developed, such as alternate wetting and drying (AWD) and aerobic rice to reduce the demand for water in

rice [7–10]. A small portion of water saved from rice planting areas can produce huge societal and environmental benefits if the water is used for higher valued uses such as urbanization, industries, or the environment [3,11–13]. Thus, it is particularly vital to establish water-saving techniques in rice farming. Various water-saving irrigation (WSI) technologies have been applied to achieve higher irrigation water use efficiency for rice in China in response to the severe situation of water insecurity [3,14]. Alternate wetting and drying (AWD), one of the most commonly practiced WSI, is a water-saving procedure for rice growing developed by the International Rice Research Institute (IRRI). In AWD, soil is dried out to some degree among irrigation or precipitation events [15] and in this way paddy fields are only intermittently irrigated during some non-critical periods [4].

The response of rice yield to AWD irrigation is highly variable. Some researchers found that AWD obtained similar or increased grain yield by 9% to 15% as compared with continuously flooded culture [16–20]. However, reduction in rice yield under AWD has also been reported [21,22]. The differences in frequency and threshold of the drying cycles of the AWD, soil-hydrological conditions, ground water table depths, and rice varieties used can all contribute to the contrasting results. Changes of the environment often lead to changes in crop growth performance and yield [20,23–26]. The optimum threshold for obtaining maximum benefits of AWD is largely site-specific depending mainly on soil type, soil texture, and the environment [3]. Several water-saving irrigation regimes have been developed in southeast China based on AWD with different water-controlled thresholds [27], such as shallow adjusting irrigation, controlled irrigation and rainwater-catching, and controlled irrigation. These irrigation regimes have different water-controlled thresholds during different rice growth stages. The difference between rainwater-catching and controlled irrigation and controlled irrigation is that the former can store more rain water than the controlled irrigation [28,29]. Drought planting with straw mulching is a water-saving irrigation regime with high water production efficiency but yield reduction risk and has not been widely used in southern China. Unfortunately, previous studies have often focused on a certain type of water-saving irrigation regime. Few researches put these water-saving irrigation regimes together to study their differences in affecting the agronomic growth performance, yield, and water use of super rice varieties. This study was conducted to quantify and compare the dynamic agronomic growth performance, yield, and irrigation water use under five different irrigation regimes of super rice varieties in southeast China. Irrigation methods have varying water-controlled thresholds in different growth stages. The experimental results should be helpful to the government to formulate irrigation guidelines in southeast China and the results could be transferred to similar environments.

## 2. Materials and Methods

### 2.1. Description of Study Area and Climatic Conditions

This study was conducted at the Key Laboratory of Efficient Irrigation–Drainage and Agricultural Soil–Water Environment in Southern China, Ministry of Education (Nanjing, latitude 31°57' N, longitude 118°50' E, and 144 m above sea level) during the rice growing seasons (May to October) of 2017 and 2018. The study area has a subtropical humid monsoon climate with an average annual temperature of 15.7 °C, annual precipitation of 1021.3 mm, annual evaporation of 900 mm, annual average sunshine hours of 2212.8 h, and a frost-free period of 220 days per year. The soil texture of the experimental site in the plowed layer is loamy clay, with organic matter of 2.40%, total nitrogen of 0.9 g kg<sup>−1</sup>, available nitrogen of 47.4 mg kg<sup>−1</sup>, total phosphorus of 33.0 mg kg<sup>−1</sup>, available phosphorus of 10.4 mg kg<sup>−1</sup>, and pH of 8.0. The saturated water content of the soil is 38.2% by mass and the soil bulk density is 1.31 g cm<sup>−3</sup>.

### 2.2. Experimental Design

The experiment was laid out in randomized complete block design, consisting of five treatments with five replications. All treatments were applied to the same pots for both years of the study. The pots were designed with a section of 40 × 40 cm<sup>2</sup> and a height of 100 cm and used for rice cultivation.

The pots also had a hydrovalve at the bottom to precisely control water volume. A sand and gravel filter layer with a thickness of 20 cm and soil with a thickness of 60 cm were loaded into each pot from the bottom up. The soil was scraped, starting from the plowed layer in the experimental site hierarchically. After scraping with a layer of about every 10 cm from top to bottom, the soil was air-dried and, then, layered and compacted according to the field bulk density. The soil in the experiment pots was expected to be close to the field soil condition of 0~60 cm in the experimental region. The rice was irrigated by sprinkler and the irrigation water was obtained from the tap water system of the lab. The measured average quality of irrigation water in 2017 and 2018 is shown in Table 1 based on the results of Huang et al. [30].

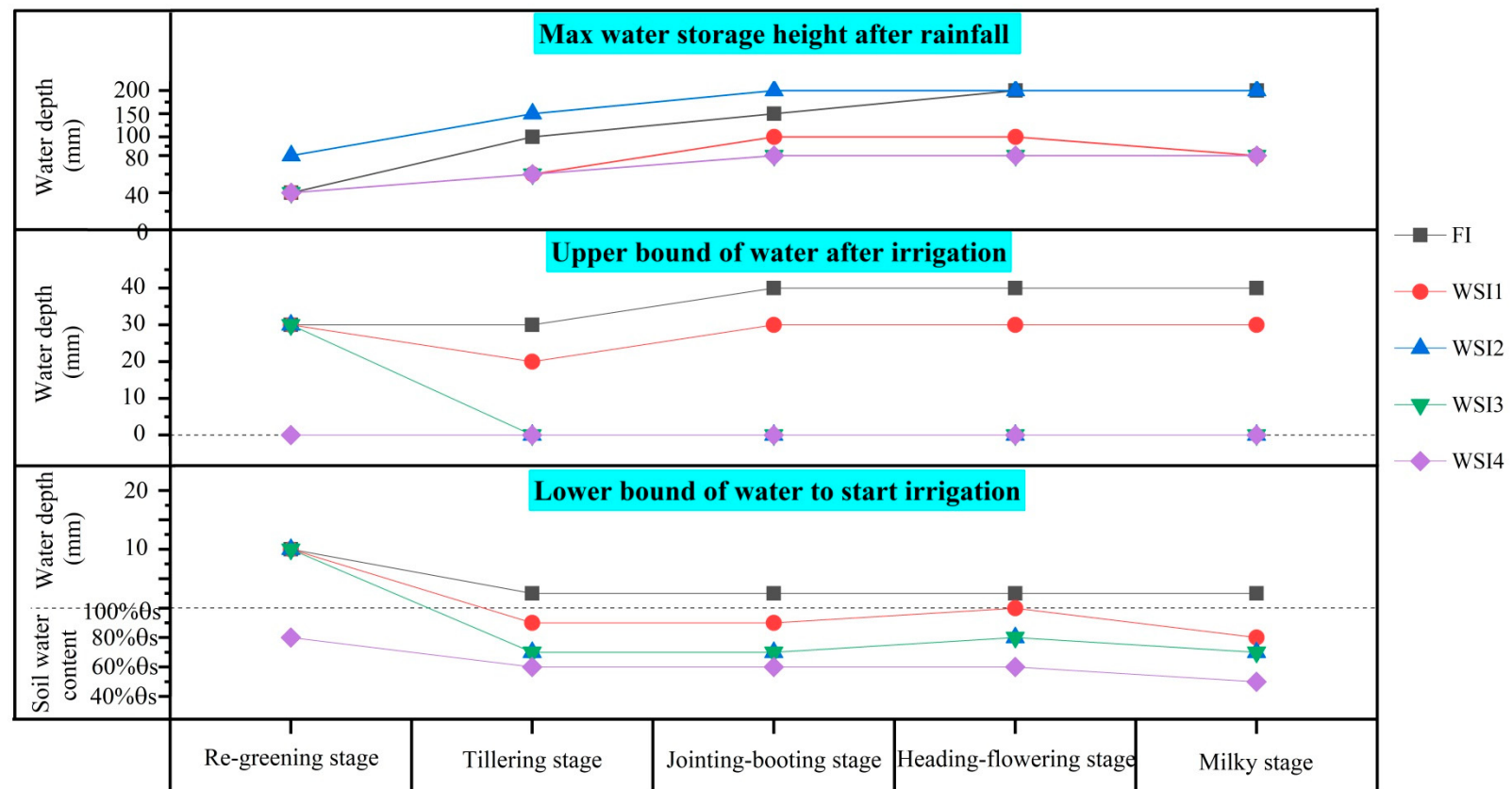
**Table 1.** Average quality of irrigation water during 2017 and 2018 season.

| Year | EC<br>(dS m <sup>-1</sup> ) | SAR<br>(mmol <sup>1/2</sup> L <sup>-11/2</sup> ) | Ca <sup>2+</sup><br>(mmol L <sup>-11</sup> ) | Mg <sup>2+</sup><br>(mmol L <sup>-11</sup> ) | Na <sup>+</sup><br>(mmol L <sup>-11</sup> ) | HCO <sub>3</sub> <sup>-</sup><br>(mmol L <sup>-11</sup> ) | Cl <sup>-</sup><br>(mmol L <sup>-11</sup> ) | SO <sub>4</sub> <sup>2-</sup><br>(mmol L <sup>-11</sup> ) |
|------|-----------------------------|--------------------------------------------------|----------------------------------------------|----------------------------------------------|---------------------------------------------|-----------------------------------------------------------|---------------------------------------------|-----------------------------------------------------------|
| 2017 | 0.3                         | 1.0                                              | 1.2                                          | 0.5                                          | 0.9                                         | 0.7                                                       | 0.6                                         | 1.6                                                       |
| 2018 | 0.3                         | 1.3                                              | 1.1                                          | 0.6                                          | 1.2                                         | 0.6                                                       | 0.8                                         | 1.8                                                       |

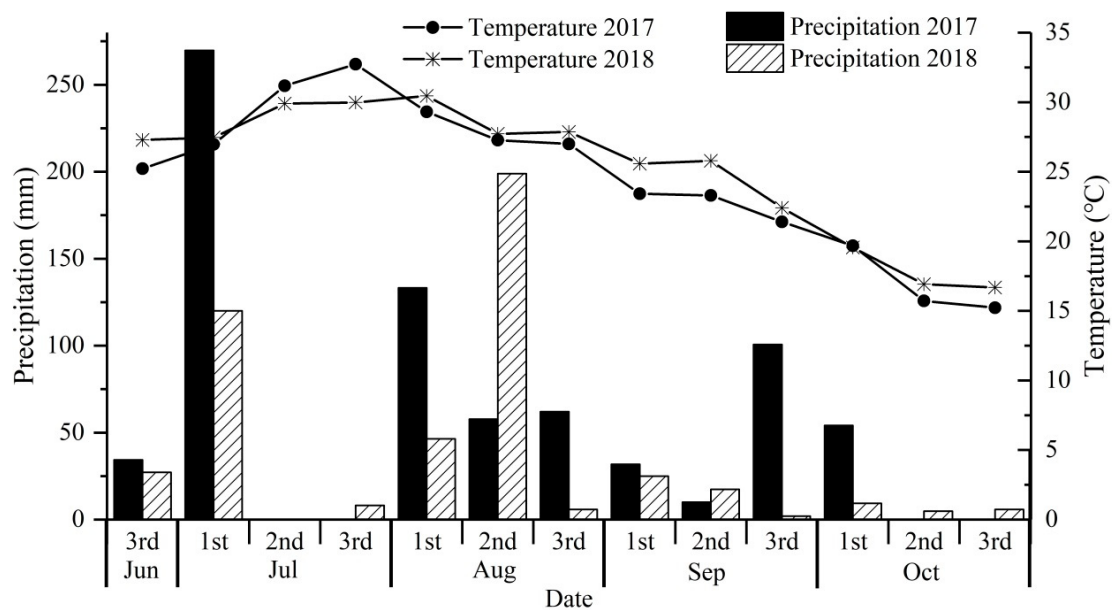
EC is electrical conductivity and SAR is sodium adsorption ratio.

Five irrigation regimes with different water-controlled thresholds in different growth stages were included in the experiment. Treatments included traditional flooding irrigation (FI, as control) and the following four water-saving irrigation (WSI) regimes: shallow adjusting irrigation (WSI1), rainwater-catching and controlled irrigation (WSI2), controlled irrigation (WSI3), and drought planting with straw mulching (WSI4). Two cm thick semi-decomposed straws were covered on the soil surface of the WSI4 treatment. Different controlled thresholds in different rice growth stages among treatments are presented in Figure 1. The rice was irrigated to the upper bound of water after irrigation when the soil water content or water depth reached the lower bound of water to start irrigation. The excess rainwater was drained to the maximum storage height of rainfall when the water level exceeded the maximum storage height of rainfall. Water percolation in the field was achieved by controlling the amount of subsurface water drainage and all treatments were exposed to natural conditions. The temperature and precipitation during the rice growth stage are shown in Figure 2.

Nanjing 5055 and Nanjing 9108, two super rice varieties widely planted locally, were grown in the pots during 2017 and 2018, respectively. Seedlings were sowed on 11 May 2017 and 20 May 2018. Plants were transplanted at six hills per pot with two seedlings per hill on 17 June 2017 and four hills per pot with three seedlings per hill on 22 June 2018. The harvest dates were 27 October 2017 and 21 October 2018. The same fertilizers were applied to all treatments. Local high-yield fertilization method was adopted in this experiment on 2017 and 2018. Total nitrogen (N) fertilization application amount each year converted into applying pure nitrogen was 244 kg/hm<sup>2</sup>, and N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O = 1:0.45:0.8. Nitrogen fertilizer was applied three times (basal fertilizer/tiller fertilizer/panicle fertilizer = 4:2:4). Phosphate fertilizer was applied once as basal fertilizer, and potassium fertilizer was applied twice (basal fertilizer/tiller fertilizer = 6:4). All basal fertilizers were incorporated in the soil at the last harrowing one day before transplanting. The pots were regularly hand weeded and pesticides were used to prevent insect and pest damage.



**Figure 1.** The water-controlled thresholds in different growth stages under different irrigation methods. ( $\theta_s$  is the saturated water content for the 0~30 cm soil layers. There was a field sunning about five days in late tillering stage).



**Figure 2.** The temperature and precipitation during the rice growth stage in 2017 and 2018.

### 2.3. Field Measurement and Sampling

A time domain reflectometer (TDR, Soil Moisture Equipment, Ltd., Corp., Goleta, CA, USA) and vertical rulers were used to monitor soil moisture and water depths, respectively. Irrigation water volumes (in liters) were measured by digital water meters (YF-S201B, Zhongjiang, Guangdong, China) installed on the pipes. Then, the irrigation water volume in mm was calculated by dividing the measured values of the digital water meters and the bottom area of the pot. The evapotranspiration is calculated following the water-balance equation [3,27,31]:

$$ET = W(t_1) - W(t_2) + P + I - D - S \quad (1)$$

where ET is crop evapotranspiration (mm),  $W(t_1)$  and  $W(t_2)$  is standing water depth (mm) or soil water content (mm) in the root zone at time  $t_1$  and  $t_2$ , P is precipitation (mm), I is irrigation (mm), D is the volume of surface drainage when the standing water depth exceeded the maximum water storage depth (mm), and S is the volume of percolation water (mm).

Plant height and tiller numbers were measured from one selected hill of each pot and, then, a total of five hills of the five replicates for each treatment were averaged. The height of each plant, before heading, was the height from the soil surface to the highest leaf tip of each hill, and after heading, it was the height from the soil surface to the highest panicle top. After the crop was harvested, grains and selected hills of rice plants were collected and the root, stem, leaf, and panicle of the rice plants were separated. The divided plants were first dried at 105 °C for 1 h and then dried at 70 °C to a constant weight for two days. Five hills of plants per treatment were randomly selected for yield components measurement. Yield components, including effective panicle number per pot, spikelet number per panicle, grain filling percentage, and 1000-grain weight were derived from the five selected hills of rice plants for each treatment. Data were averaged over all subsamples for each treatment. Irrigation water use efficiency (IWUE) was calculated as grain yield divided by total amount of irrigated water as follows:  $IWUE = \text{grain yield} / \text{cumulative irrigation water supply}$ .

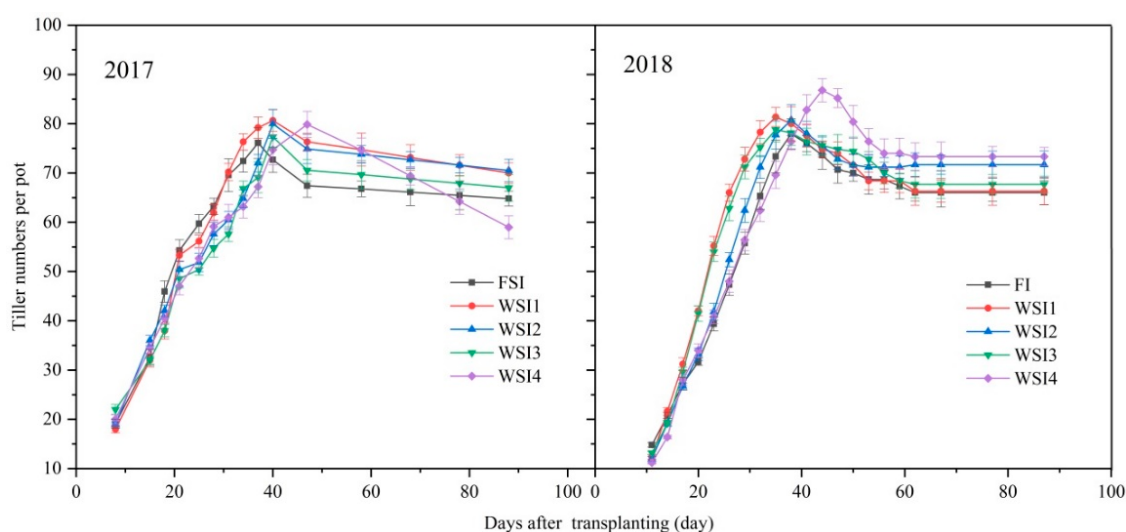
### 2.4. Statistical Analysis

Data were analyzed by one-way ANOVA with least significant difference (LSD) test at the 0.05 probability level. All statistical analyses were performed using standard procedures for a randomized plot design (SPSS 22.0, SPSS Inc., Chicago, IL, USA).

### 3. Results

#### 3.1. Dynamic Variations of Rice Tillers

Figure 3 shows the dynamic variation characteristic of tiller numbers in 2017 and 2018. The tillering patterns under the five irrigation regimes during the whole rice growth stage were basically the same, and they all showed the characteristics of rapidly increasing first and, then, gradually decreasing. However, the WSI treatment delayed the time of reaching the maximum number of tillers in both years. The maximum number of tillers for WSI1, WSI2, and WSI3 treatments were observed 40 days after transplanting and for the WSI4 treatment it was observed 47 days after transplanting in 2017. The dates to reach maximum number of tillers under WSI treatments were all later than that of the FI treatment whose maximum number of tillers was observed 37 days after transplanting. In 2018, the maximum number of tillers was observed 37 days after transplanting under FI and WSI3, but 41 days after transplanting under WSI2, and 44 days after transplanting under WSI4. The productive tiller numbers under FI were the lowest among all treatments in both years. Thus, FI had the lowest percentage of productive tillers (79.40% in 2017 and 84.08% in 2018) among all treatments in both years (except WSI4 in 2017 as a result of severe drought in late growth stage).

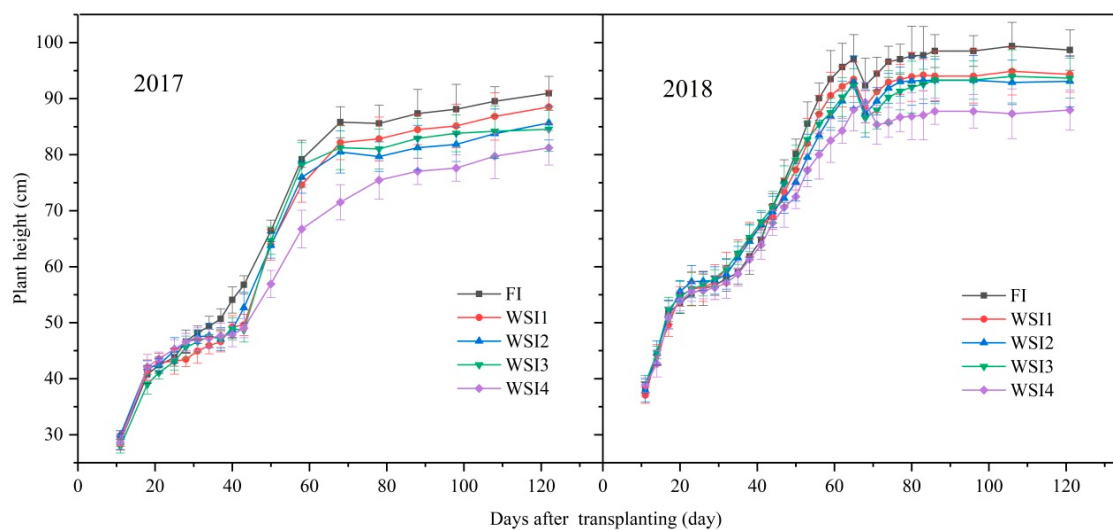


**Figure 3.** The variation of the tiller numbers per pot in 2017 and 2018.

#### 3.2. Dynamic Variations of Rice Plant Height

The dynamic variation characteristic of plant height in 2017 and 2018 is shown in Figure 4. The trend of variation of rice plant height was consistent. The plant height increased rapidly during the early tillering stage and, then, grew slowly during the middle and late tillering stages when vigorous tillering took place. The plant height increased most rapidly during the jointing-booting stage and reached the highest value during the heading-flowering stage. The plant height was less variable and tended to be stable during the milky stage and ripening stage, which coincided with the time of the reproductive stage.

Rice plants exposed to WSI treatments were significantly shorter than plants receiving continuous water treatments (FI) after the tillering stage. Among the WSI treatments, the rice plant height of WSI4 was significantly shorter than that of WSI1, WSI2, and WSI3 in both years. The final plant height was significantly higher under FI than that under WSI treatments during both years, as maximum plant height of 90.95 cm in 2017 and 98.68 cm in 2018 were observed under FI. Among the WSI treatments, the final plant height showed an order of WSI1 > WSI2 and WSI3 > WSI4 in both years but there was no significant difference between WSI2 and WSI3.



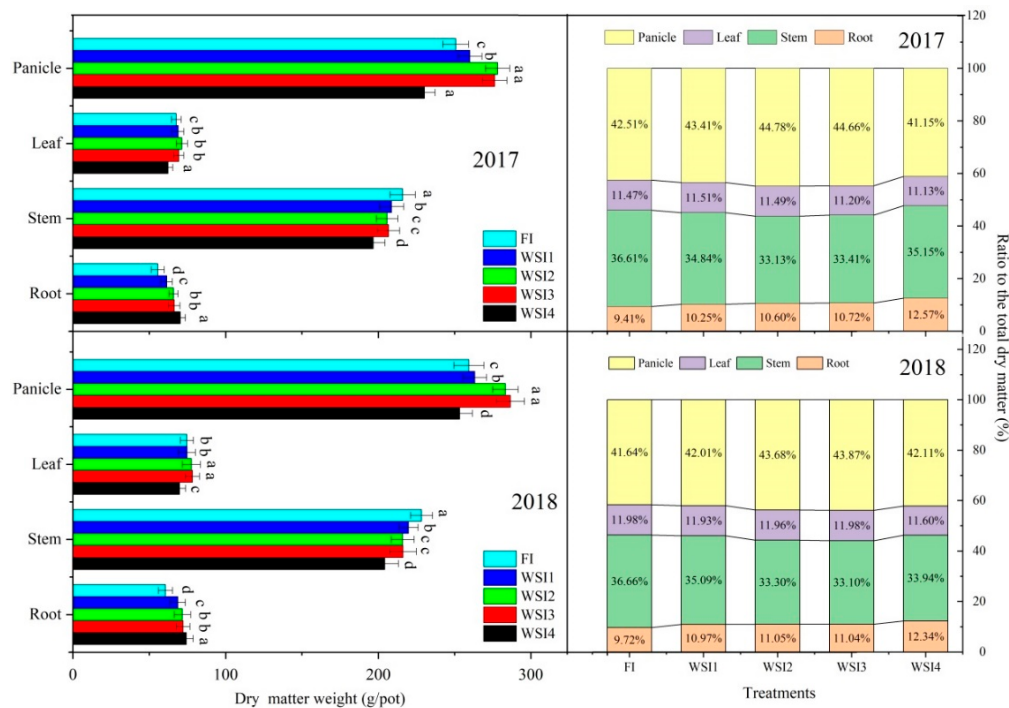
**Figure 4.** The variation of the rice plant height in 2017 and 2018.

### 3.3. Dry Matter Yield, Grain Yield, and Yield Components

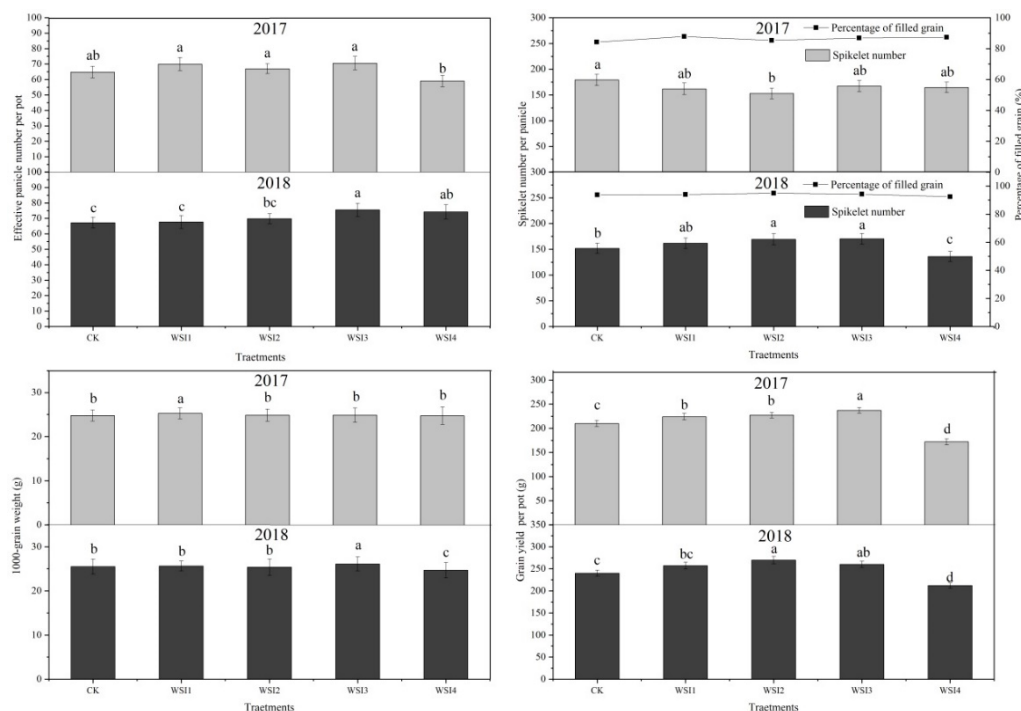
Figure 5 shows the dry matter yield of different parts of the rice plant (root, stem, leaf, and panicle) per pot of each treatment. WSI2 and WSI3 increased the total dry matter yield by 5.31% and 4.87% in 2017 and 4.12% and 4.88% in 2018, respectively, as compared with FI. However, WSI4 decreased the total dry matter yield by 5.12% in 2017 and 3.39% in 2018, respectively. There was no significant difference in the total dry matter yield between WSI1 and FI. The WSI treatments significantly increased the dry matter weight of root as compared with FI. The dry matter weight of root increased by 10.52% and 13.51% for WSI1, 18.64% and 18.38% for WSI2, 19.43% and 19.12% for WSI3, and 26.73% and 22.61% for WSI4 as compared with FI in 2017 and 2018, respectively. However, the dry matter weight of stem decreased by 3.38% and 3.72% for WSI1, 4.72% and 5.42% for WSI2, 4.30% and 5.29% for WSI3, and 8.93% and 10.55% for WSI4 as compared with FI in 2017 and 2018, respectively. WSI4 significantly decreased the dry matter weight of leaf by 7.87% in 2017 and 6.39% in 2018 as compared with FI but WSI1, WSI2, and WSI3 increased the dry matter weight of leaf by 1.91% and 0.24%, 5.50% and 4.03%, and 2.45% and 4.97% in 2017 and 2018, respectively. WSI4 showed the lowest panicle dry matter yield among treatments but WSI1, WSI2, and WSI3 all increased the panicle dry matter yield as compared with FI in both years.

The rice yields of the WSI1, WSI2, and WSI3 all increased as compared with the FI treatment, in 2017 and 2018 (Figure 6). The rice yields increased by 6.62% for WSI1, 8.21% for WSI2, and 12.91% for WSI3 in 2017, and 7.20% for WSI1, 12.39% for WSI2, and 8.30% for WSI3 in 2018. However, WSI4 decreased the rice yield by 18.10% and 11.69% as compared with FI treatment in 2017 and 2018, respectively. The number of effective panicles was higher for the WSI1, WSI2, and WSI3 treatments than for the FI treatments in both years. The effective panicle number of WSI4 was significantly lower than FI, in 2017, due to severe water deficit and became similar to WSI3, in 2018, as a result of adding more irrigation water.

The percentage of filled grains was 84.23%–87.81% in 2017 and 92.39%–94.95% in 2018 and there was no significant difference among treatments. This was consistent with the result of Belder et al. [32] who found that the percentage of filled grains was also not significantly affected by the water regime. Under different irrigation regimes, the change of spikelet number per panicle and the 1000-grain weight was not completely the same during the two years.



**Figure 5.** The dry matter yield of different parts of the rice plant and their ratio to the total dry matter weight in 2017 and 2018.



**Figure 6.** Grain yield and its components of different irrigation regimes in 2017 and 2018.

### 3.4. Crop Evapotranspiration, Irrigation, and Irrigation Water Use Efficiencies

The evapotranspiration of different irrigation regimes in different growth stages is shown in Table 2. The evapotranspiration of the tillering, jointing-booting, heading-flowering, and milky stages accounts for more than 88% of the total evapotranspiration. The jointing-booting stage was the most vigorous period of evapotranspiration, accounting for 31.81% to 36.16% of the total evapotranspiration in both years. Among the different treatments, FI had the maximum total evapotranspiration (796.4 mm

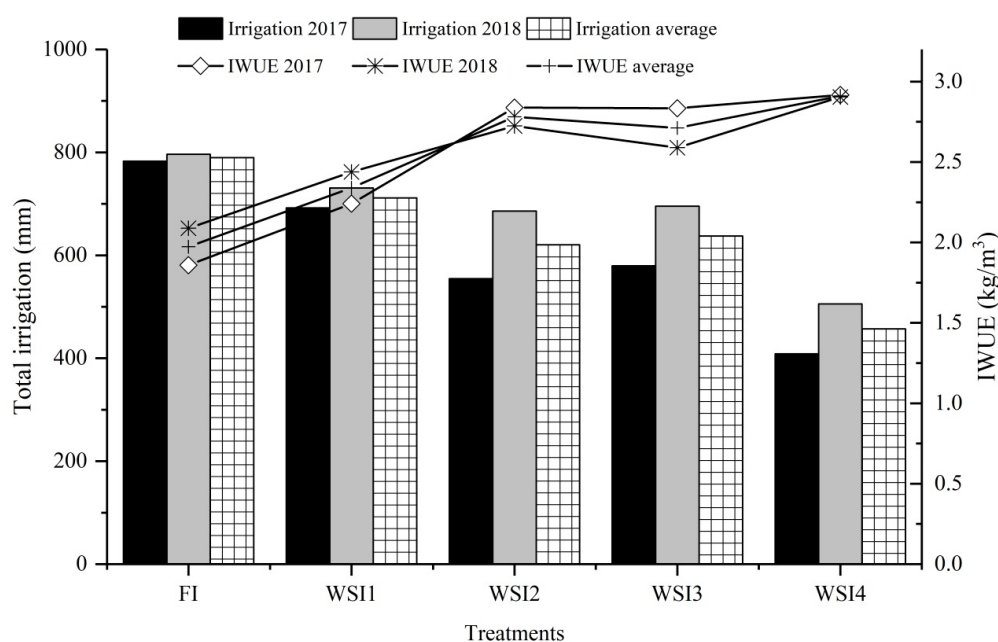
in 2017 and 814.2 mm in 2018). WSI1, WSI2, WSI3, and WSI4 decreased the total evapotranspiration by 8.48% and 10.27%, 10.12% and 9.97%, 16.22% and 13.79%, and 23.72% and 20.58% as compared with FI, in 2017 and 2018, respectively. The decrease of evapotranspiration under WSI treatments mainly happened in the tillering, jointing-booting, heading-flowering, and milky stages. Despite the decrease of evapotranspiration, WSI1, WSI2 and WSI3 did not result in the decrease of rice yield.

**Table 2.** The evapotranspiration of different irrigation regimes in different growth stages.

| Year | Treatments | R-G    | T        | J-B     | H-F      | M       | R      | Total   |
|------|------------|--------|----------|---------|----------|---------|--------|---------|
| 2017 | FI         | 31.5 a | 121.7 a  | 283.2 a | 188.7 a  | 137.8 a | 33.5 b | 796.4 a |
|      | WSI1       | 30.7 a | 107.2 b  | 262.6 b | 162.1 b  | 137 a   | 29.3 b | 728.9 b |
|      | WSI2       | 29.8 a | 112.8 b  | 247.3 c | 155.3 bc | 125.6 b | 45 a   | 715.8 c |
|      | WSI3       | 31.2 a | 93.9 c   | 233.9 d | 152.7 c  | 113.2 c | 42.3 a | 667.2 d |
|      | WSI4       | 29.6 a | 91.8 c   | 205.2 e | 127.5 d  | 117.8 c | 35.6 b | 607.5 e |
| 2018 | FI         | 38.2 a | 137.3 a  | 260.2 a | 233.7 a  | 122.2 a | 22.6 a | 814.2 a |
|      | WSI1       | 39.1 a | 116.9 c  | 232.4 c | 210.4 b  | 112.3 b | 19.5 a | 730.6 b |
|      | WSI2       | 37.6 a | 128.2 b  | 248.7 b | 197.7 c  | 97.6 c  | 23.2 a | 733 b   |
|      | WSI3       | 35.5 a | 122.1 bc | 241.3 b | 184.3 d  | 95.9 c  | 22.8 a | 701.9 c |
|      | WSI4       | 35.4 a | 118.6 c  | 233.8 c | 148.6 e  | 89.7 c  | 20.5 a | 646.6 d |

Note: R-G, T, J-B, H-F, M, R mean the rice growth stage of re-greening stage, tillering stage, jointing-booting stage, heading-flowering stage, milky stage, ripening stage, respectively.

The total irrigation water input during the whole rice growth stage and the irrigation water use efficiency of each treatment are shown in Figure 7. The total irrigation water input followed an order of FI > WSI1 > WSI3 > WSI2 > WSI4 during both years. The irrigation water application for the whole growing season was 87.23%~87.90% for WSI1, 70.44%~81.87% for WSI2, 73.61%~83.00% for WSI3, and 52.89%~60.33% for WSI4 of that applied to FI, respectively, from 2017 to 2018. The WSI treatments showed significant water saving effect as compared with FI treatment. During the two years, WSI treatments significantly increased the irrigation water use efficiency by 18.59% (two-year average, the same below) for WSI1, 40.95% for WSI2, 37.42% for WSI3, and 47.50% for WSI4 as compared with FI, respectively. Although WSI4 has the most significant water-saving effect with the highest irrigation water use efficiency, the rice yield was markedly reduced as compared with other treatments.



**Figure 7.** The total irrigation input and the irrigation water use efficiency of each treatment.

#### 4. Discussion

The application of water-saving techniques affects the soil condition of paddy fields and the nutrient cycle in the agroecosystem, and thus crop growth and yield [32,33]. The agronomic growth dynamic performance, rice growth, yield, and water use under different irrigation methods with different water-controlled thresholds in different growth stages using super rice varieties was investigated in this study. In this study, we show that different irrigation regimes do not change the basic rules of rice tillering but do affect the increase or decrease extent of rice tillers, which ultimately affect the effective tillering rate. There is a possibility that WSI treatments delay the time of reaching the maximum number of tillers, and the appearance time of the maximum tiller number would be later when the water control is drier. A study by Wei et al. [34] reported that the maximum number of tillers usually occurred at the late tillering or jointing stage (approximately 40 days after transplanting) and controlled irrigation with straw returning delayed the peak time of tillers, which is in agreement with the results of this experiment. In this study, WSI inhibited the increase of rice plant height to some extent and the greater the degree of drought, the more obvious the inhibition was. Similar results were found in the Taihu region of China by Wei et al. [34] and Shao et al. [7]. The inability of roots to acclimatize to the changes of water condition under water-saving irrigation influences rice growth, and thereby dry matter production [7]. The WSI treatments increased the root dry matter weight but decreased the stem dry matter weight as compared with FI, in this study. Among the five treatments, the dry matter yield of root under FI showed the lowest ratio to the total dry matter weight, which was only 9.41% in 2017 and 9.72% in 2018 (Figure 5). However, the ratio was 10.25% to 12.57% under WSI treatments and the WSI4 treatment showed the highest ratio of 12.57% in 2017 and 12.34% in 2018, respectively. The application of water-saving irrigation resulted in the trend of drier soil moisture, and further promoted the plant root system to grow deeper to adapt to the situation.

The application of water-saving irrigation resulted in highly variable response of rice yield. Similar or increased grain yield by 9% to 15% as compared with traditional flood irrigation was found by some researchers [16,17,20]. However, Bouman and Tuong [21] and Xu et al. [22] reported the reduction in rice yield under water-saving irrigation. In this experiment, we observed an increase of 6.62% to 12.91% of rice yield under WSI1, WSI2, and WSI3 but a yield reduction of 11.69% to 18.10% under WSI4 as compared with FI. WSI4 caused severe drought condition in some rice growth stages, which resulted in the heavy yield reduction. The differences in frequency and threshold of the drying cycles of the water-saving irrigation influenced the soil-hydrological conditions and, then, influenced the growth process of rice, resulting in the change of yield and yield components. WSI2 and WSI3 significantly increased the effective panicle number as compared with FI. Cao et al. [35] and Yang et al. [36] found that severe water deficit was the major reason for low yield by decreasing spikelet number, which was identical with our results in 2018. There was no significant difference in 1000-grain weight among the treatments. Evapotranspiration is an important part of the field water cycle throughout the whole process of crop growth and development [37]. WSI significantly decreased the crop evapotranspiration during the rice growth period and reduction of evapotranspiration is an important factor for water saving under WSI. Similar results have been reported by Alberto et al. [37] and Liu et al. [38]. The decrease of the evapotranspiration under the WSI treatments mainly occurred during the tillering stage, jointing-booting stage, heading-flowering stage, and milky stage, correspondingly, the alternate wetting and drying cycle control under WSI, WSI1, WSI2, and WSI3 did not cause reduction of rice yield despite the decrease of evapotranspiration. Comprehensive consideration of rice growth, yield, and irrigation water use, WSI2 and WSI3, showed more appropriate results, indicating great promotion potential in southeast China. Furthermore, the experiment of this study was conducted in designed pots with quite small size, which differs significantly from the environmental conditions of actual fields. Actual field experiments are expected to verify the exploration of our pot experiment, which should be fully considered in future research.

## 5. Conclusions

The agronomic growth dynamic performance, rice growth, yield, and water use were remarkably affected by the application of water-saving techniques. Different irrigation methods with different water-controlled thresholds in different growth stages were investigated in this study using super rice varieties. In this study, the WSI treatments obviously delayed the time of reaching the maximum number of tillers and inhibited the increase of rice plant height to some extent, however, they increased the productive tiller numbers as compared with FI in both years. The application of WSI promoted the plant root system to grow deeper to adapt to the situation and increased the root dry matter production. WSI significantly decreased the crop evapotranspiration during the rice growth period. WSI1, WSI2, and WSI3 not only saved water but also increased the rice yield to some extent (increased by 6.62%~12.91% as compared with FI) and WSI2 and WSI3 significantly increased the effective panicle number. The irrigation water use efficiency followed an order of WSI4 > WSI2 > WSI3 > WSI1 > FI, in both years. Comprehensive consideration of rice growth, yield, and irrigation water use, WSI2 and WSI3, showed more appropriate results, indicating great promotion potential in southeast China. In summary, the results showed that WSI2 was the most optimal irrigation regime considering yield and water saving effect, followed by WSI3. WSI1 and WSI4 should be further optimized to achieve the need for water-saving and high-yield.

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## References

1. Wu, X.H.; Wang, W.; Xie, X.L.; Yin, C.M.; Xie, K.J. Photosynthetic and yield responses of rice (*Oryza sativa* L.) to different water management strategies in subtropical China. *Photosynthetica* **2018**, *56*, 1031–1038. [\[CrossRef\]](#)
2. Zheng, J.; Chen, T.; Chi, D.; Xia, G.; Wu, Q.; Liu, G.; Chen, W.; Meng, W.; Chen, Y.; Siddique, K.H.J.A. Influence of Zeolite and Phosphorus Applications on Water Use, P Uptake and Yield in Rice under Different Irrigation Managements. *Agronomy* **2019**, *9*, 537. [\[CrossRef\]](#)
3. Cabangon, R.J.; Tuong, T.P.; Castillo, E.G.; Bao, L.X.; Lu, G.; Wang, G.; Cui, Y.; Bouman, B.A.M.; Li, Y.; Chen, C.; et al. Effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. *Paddy Water Environ.* **2004**, *2*, 195–206. [\[CrossRef\]](#)
4. Yamaguchi, T.; Tuan, L.M.; Minamikawa, K.; Yokoyama, S. Assessment of the relationship between adoption of a knowledge-intensive water-saving technique and irrigation conditions in the Mekong Delta of Vietnam. *Agric. Water Manag.* **2019**, *212*, 162–171. [\[CrossRef\]](#)
5. Yan, T.; Wang, J.; Huang, J. Urbanization, agricultural water use, and regional and national crop production in China. *Ecol. Model.* **2015**, *318*, 226–235. [\[CrossRef\]](#)
6. Li, Q.; Bian, C.; Liu, X.; Ma, C.; Liu, Q. Winter wheat grain yield and water use efficiency in wide-precision planting pattern under deficit irrigation in North China Plain. *Agric. Water Manag.* **2015**, *153*, 71–76. [\[CrossRef\]](#)
7. Shao, G.; Cui, J.; Yu, S.e.; Lu, B.; Brian, B.J.; Ding, J.; She, D. Impacts of controlled irrigation and drainage on the yield and physiological attributes of rice. *Agric. Water Manag.* **2015**, *149*, 156–165. [\[CrossRef\]](#)

8. Bouman, B. A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agric. Syst.* **2007**, *93*, 43–60. [[CrossRef](#)]
9. Sang, H.; Jiao, X.; Wang, S.; Guo, W.; Salahou, M.K.; Liu, K. Effects of micro-nano bubble aerated irrigation and nitrogen fertilizer level on tillering, nitrogen uptake and utilization of early rice. *Plant Soil Environ.* **2018**, *64*, 297–302.
10. Aziz, O.; Bin, L.; Imtiaz, M.; Chen, J.; He, Y.; Lin, L.; Ali, S.; Riaz, M.; Mehmood, S.; Rizwan, M.; et al. Irrigation methods affect water productivity, grain yield, and growth responses of rice at different levels of nitrogen. *J. Soil Water Conserv.* **2018**, *73*, 329–336. [[CrossRef](#)]
11. Rahman, S.M.; Kakuda, K.-i.; Sasaki, Y.; Makabe-Sasaki, S.; Ando, H. Early growth stage water management effects on the fate of inorganic N, growth and yield in rice. *Soil Sci. Plant Nutr.* **2013**, *59*, 921–932. [[CrossRef](#)]
12. He, C. Effects of furrow irrigation on the growth, production, and water use efficiency of direct sowing rice. *Sci. World J.* **2010**, *10*, 1483–1497. [[CrossRef](#)] [[PubMed](#)]
13. Brar, A.S.; Buttar, G.S.; Jhanji, D.; Sharma, N.; Vashist, K.K.; Mahal, S.S.; Deol, J.S.; Singh, G. Water productivity, energy and economic analysis of transplanting methods with different irrigation regimes in Basmati rice (*Oryza sativa* L.) under north-western India. *Agric. Water Manag.* **2015**, *158*, 189–195. [[CrossRef](#)]
14. Yang, S.; Xiao, Y.; Xu, J.; Liu, X. Effect of straw return on soil respiration and NEE of paddy fields under water-saving irrigation. *PLoS ONE* **2018**, *13*, e0204597. [[CrossRef](#)]
15. Mao, Z. Water-efficient irrigation regimes of rice in China. In Proceedings of the International Rice Research Conference, Los Banos, Philippines, 31 March–3 April 2000.
16. Escasinas, R.O.; Zamora, O.B. Agronomic response of lowland rice PSB Rc 18 (*Oryza sativa* L.) to different water, spacing and nutrient management. *Philipp J Crop Sci* **2011**, *36*, 37–46.
17. He, H.; Yang, R.; Jia, B.; Chen, L.; Fan, H.; Cui, J.; Yang, D.; Li, M.; Ma, F.-Y. Rice Photosynthetic Productivity and PSII Photochemistry under Nonflooded Irrigation. *Sci. World J.* **2014**, *2014*. [[CrossRef](#)]
18. Carrijo, D.R.; Akbar, N.; Reis, A.F.; Li, C.; Gaudin, A.C.; Parikh, S.J.; Green, P.G.; Linquist, B.A. Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Res.* **2018**, *222*, 101–110. [[CrossRef](#)]
19. Nyamai, M.; Mati, B.; Home, P.; Odongo, B.; Wanjogu, R.; Thurair, E. Improving land and water productivity in basin rice cultivation in Kenya through System of Rice Intensification (SRI). *Agric. Eng. Int. CIGR J.* **2012**, *14*, 1–9.
20. Yao, F.; Huang, J.; Cui, K.; Nie, L.; Xiang, J.; Liu, X.; Wu, W.; Chen, M.; Peng, S. Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crops Res.* **2012**, *126*, 16–22. [[CrossRef](#)]
21. Bouman, B.; Tuong, T.P. Field water management to save water and increase its productivity in irrigated lowland rice. *Agric. Water Manag.* **2001**, *49*, 11–30. [[CrossRef](#)]
22. Xu, Y.; Ge, J.; Tian, S.; Li, S.; Nguy-Robertson, A.L.; Zhan, M.; Cao, C. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Sci. Total Environ.* **2015**, *505*, 1043–1052. [[CrossRef](#)] [[PubMed](#)]
23. Kakar, K.; Xuan, T.D.; Quan, N.V.; Wafa, I.K.; Tran, H.-D.; Khanh, T.D.; Dat, T.D.J.A. Efficacy of N-methyl-N-nitrosourea (MNU) Mutation on Enhancing the Yield and Quality of Rice. *Agriculture* **2019**, *9*, 212. [[CrossRef](#)]
24. Behera, S.K.; Panda, R.K. Effect of fertilization on crop responses and solute transport for rice crop in a sub-humid and sub-tropical region. *Paddy Water Environ.* **2012**, *11*, 227–239. [[CrossRef](#)]
25. Yang, J.; Liu, K.; Wang, Z.; Du, Y.; Zhang, J. Water-saving and high-yielding irrigation for lowland rice by controlling limiting values of soil water potential. *J. Integr. Plant Biol.* **2007**, *49*, 1445–1454. [[CrossRef](#)]
26. Westendorff, N.d.R.; Agostinetto, D.; Ulguim, A.d.R.; Perboni, L.T.; Silva, B.M.d. Yield loss and economic thresholds of yellow nutsedge in irrigated rice as a function of the onset of flood irrigation. *Bragantia* **2014**, *73*, 32–38. [[CrossRef](#)]
27. Peng, S.-Z.; Yang, S.-H.; Xu, J.-Z.; Luo, Y.-F.; Hou, H.-J. Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. *Paddy Water Environ.* **2011**, *9*, 333–342. [[CrossRef](#)]
28. Zheng, C.X.; Zhang, Z.Y.; Wu, Y.Y.; Mwiya, R. Response of Vertical Migration and Leaching of Nitrogen in Percolation Water of Paddy Fields under Water-Saving Irrigation and Straw Return Conditions. *Water* **2019**, *11*, 868. [[CrossRef](#)]

29. Lu, H.; Qi, X.; Guo, X.; Towa, J.; Zhen, B.; Qiao, D.; Wang, Z.; Yang, B.; Han, Y. Canopy Light Utilization and Yield of Rice under Rain-Catching and Controlled Irrigation. *Water* **2018**, *10*, 1340. [[CrossRef](#)]
30. Huang, M.; Zhang, Z.; Zhai, Y.; Lu, P.; Zhu, C. Effect of Straw Biochar on Soil Properties and Wheat Production under Saline Water Irrigation. *Agronomy* **2019**, *9*, 457. [[CrossRef](#)]
31. Liu, B.; Cui, Y.; Shi, Y.; Cai, X.; Luo, Y.; Zhang, L. Comparison of evapotranspiration measurements between eddy covariance and lysimeters in paddy fields under alternate wetting and drying irrigation. *Paddy Water Environ.* **2019**, *17*, 725–739. [[CrossRef](#)]
32. Belder, P.; Bouman, B.; Cabangon, R.; Guoan, L.; Quilang, E.; Yuanhua, L.; Spiertz, J.; Tuong, T. Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agric. Water Manag.* **2004**, *65*, 193–210. [[CrossRef](#)]
33. Ullah, H.; Mohammadi, A.; Datta, A. Growth, yield and water productivity of selected lowland Thai rice varieties under different cultivation methods and alternate wetting and drying irrigation. *Ann. Appl. Biol.* **2018**, *173*, 302–312. [[CrossRef](#)]
34. Wei, Q.; Xu, J.; Sun, L.; Wang, H.; Lv, Y.; Li, Y.; Hameed, F. Effects of straw returning on rice growth and yield under water-saving irrigation. *Chilean J. Agric. Res.* **2019**, *79*, 66–74. [[CrossRef](#)]
35. Cao, X.; Zhong, C.; Sajid, H.; Zhu, L.; Zhang, J.; Wu, L.; Jin, Q. Effects of watering regime and nitrogen application rate on the photosynthetic parameters, physiological characteristics, and agronomic traits of rice. *Acta Physiol. Plant.* **2017**, *39*, 135. [[CrossRef](#)]
36. Yang, J.; Zhang, J.; Wang, Z.; Liu, L.; Zhu, Q. Postanthesis water deficits enhance grain filling in two-line hybrid rice. *Crop Sci.* **2003**, *43*, 2099–2108. [[CrossRef](#)]
37. Alberto, M.C.R.; Wassmann, R.; Hirano, T.; Miyata, A.; Hatano, R.; Kumar, A.; Padre, A.; Amante, M. Comparisons of energy balance and evapotranspiration between flooded and aerobic rice fields in the Philippines. *Agric. Water Manag.* **2011**, *98*, 1417–1430. [[CrossRef](#)]
38. Liu, X.; Xu, J.; Yang, S.; Zhang, J. Rice evapotranspiration at the field and canopy scales under water-saving irrigation. *Meteorol. Atmos. Phys.* **2017**, *130*, 227–240. [[CrossRef](#)]



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