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Article

Effects of Waterlogging on Rice Growth at Jointing–Booting Stage

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Abstract: The rice waterlogging stress test was conducted at the experimental base of the College of Agriculture, Yangtze University, using Yangxian You 418 as the test subject, in order to investigate the impact of waterlogging on rice growth during the period from July to August each year. Six waterlogging stress tests with different waterlogging depth (1/4 plant height (1/4PH), 2/4 PH, and 3/4 PH) and duration (5 d and 7 d) were set up at the jointing–booting stage of rice (T1: 1/4 PH, 7 d; T2: 2/4 PH, 7 d; T3: 3/4 PH, 7 d; T4: 1/4 PH, 5 d; T5: 2/4 PH, 5 d; T6: 3/4 PH, 5 d;) with shallow water irrigation (CK) as control. The plant height, population leaf area, above-ground dry matter, and the yield of rice were measured. The correlation between the waterlogging depth and rice yield reduction was analyzed, and the flood disaster threshold index of rice was established. The results showed that at the end of stress, the plant height of all waterlogged treatments exceeded CK, and the plant height of T3 and T6 treatments significantly increased by 31.90% and 15.93%, respectively. The leaf area of rice treated with T1, T3, T4, and T5 was higher than CK ($p < 0.05$), and the above-ground dry matter of rice treated with T2, T3, T4, T5, and T6 was higher than CK ($p < 0.05$). When normal irrigation was restored to the maturity stage, the plant height of all rice treated with waterlogging was still higher than CK ($p < 0.05$). However, as the degree of waterlogging increased, rice yield decreased significantly, with a notable reduction of 31.68% observed in the T3 treatment compared to CK. Assuming a drainage index based on a 20% decrease in rice yield, it is imperative that the ratio of flooded depth to plant height remains below 37% when waterlogging persists for 7 days in rice cultivation. These research findings offer crucial scientific insights for implementing effective drainage management measures during flood disasters in rice paddies.

Keywords: waterlogging; rice; yield; above-ground dry matter weight

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1. Introduction

According to the World Meteorological Organization, extreme climate-induced water disasters accounted for over half of all disasters in the 50 years between 1970 and 2019. The gradual intensification of global warming has led to increasingly severe extreme flood disasters [1,2]. The middle and lower reaches of the Yangtze River, especially the Jianghan Plain, are crucial rice cultivation areas in China, with an annual rice planting area of 667,000 hm^2. However, due to its low-lying geography and the convergence of surface and groundwater, coupled with frequent concentrated precipitation during the Meiyu period (occurring in about 7 to 8 out of every 10 years) [3], this region often experiences waterlogging during the jointing and booting stages of rice growth [4]. Such floods can impede rice growth and development, leading to decreased yields or even total crop failure [5–7], thus posing a significant threat to rice production safety in the area. As a result, scholars both domestically and internationally have conducted field and pot experiments to assess the impact of waterlogging stress on various morphological indices, physiological indicators, and the yield potential of rice. Previous research has shown that floods of different depths and durations during various growth stages can have diverse effects on rice growth and yield [8–10]. Waterlogging stress affects parameters such as plant height, tillering number, growth duration, and dry matter allocation coefficient for each organ to varying degrees [11–14]. Flooding stress can lead to obvious yield reduction or even the loss of rice harvest. The main reason for the decrease in rice yield due to flooding stress was the decrease in grain number per panicle and seed setting rate [15]. Studies have shown that the order of the effect of flooding stress on yield components is effective panicle number > grain number per panicle > seed setting rate > thousand-grain mass, and the yield decreases by more than 30% [16]. For instance, experiencing waterlogging stress during the booting stage of the rice development cycle significantly increases plant height but decreases stalk quality [17]. Long-term flooding stress can reduce rice yield and rice quality [18]. However, there are few studies on the flood tolerance threshold of rice in the key growth period in southern China. In this study, different waterlogging depths and durations were set up to observe the changes in rice growth indexes and yield factors under different waterlogging treatments, analyze the effects of different waterlogging treatments on rice growth, construct a linear regression equation of the relative yield change rate and R_{WH} (R_{WH}: ratio of waterlogging depth to plant height), and explore the waterlogging threshold of rice at the jointing–booting stage. It can provide a theoretical basis for rice field water management in southern China and has great significance for ensuring national food security.

2. Materials and Methods

2.1. Materials

Yangxian You 418 (Suxiandao 200501, Agricultural Science Research Institute of Lixiahe Region, Yangzhou, China) was bred in 2002 through a combination of Yangindica 2A× Yanghui 418 in Lixiahe area of Jiangsu Province. It belongs to three lines of indica hybrid rice. Rice was planted for one season in the middle and lower reaches of the Yangtze River. The plant height of this variety is about 115 cm, and the whole growth period is about 143 days. The plant type is compact; the tillering ability and lodging resistance are strong. The seedling age was 30–35 days, and the planting density was 270,000–300,000 holes per hectare.

2.2. Experiment Design

The test site is located at the experimental base of the College of Agriculture, Yangtze University, Jingzhou City, Hubei Province (30°21′ N, 112°09′ E), which belongs to the eastern monsoon agri-climate region, the north subtropical agri-climate zone, and the middle and lower reaches of the Yangtze River agri-climate region. The average annual temperature is 16.5 °C, the average annual sunshine duration is 1742.4 h, and the average annual precipitation is 1089 mm. The distribution of rainfall is uneven, and the frequency of flood disasters is high.

Barrel planting was used in 2019. The tested soil was taken from the 0–30 cm surface layer near the rice field in the test area, with a pH value of 7.4, organic matter of 15.4 $g \cdot kg^{-1}$, alkali-hydrolyzed nitrogen of 150.6 $mg \cdot kg^{-1}$, available phosphorus of 14.5 $mg \cdot kg^{-1}$, and available potassium of 84.7 $mg \cdot kg^{-1}$. After drying, breaking, and sifting, uniform fertilization was applied. The bottom diameter of the test bucket was 27.5 cm, the upper diameter was 37.5 cm, the depth of the bucket was 33.5 cm, and the air-dried soil was 20 kg per barrel. The fertilization amount was reduced to pure N 3.0 g, P_2O_5 2.0 g, K_2O 2.0 g. For the pot test breeding on 25 April 2019, when the seedlings grew to three leaves, seedlings of roughly the same size for transplanting were selected (1 June 2019). The planting density was 270,000–300,000 holes per hectare. Six holes were planted in each barrel, and two plants were transplanted in each hole.

The rainfall in the Hanjiang Plain was mainly concentrated in July and August, and the frequency of 50–100 mm precipitation was relatively high [19]. The allowable waterlogging duration of the jointing period is 5–7 days [20], which falls precisely at the jointing and booting stage of middle rice and makes it easy to cause rice waterlogging. Therefore, waterlogging stress was set at the jointing–booting stage of rice in this experiment, according to the existing rice waterlogging stress test scheme [21,22]. In this experiment, six waterlogging treatments and one control treatment were set up. Two factors of waterlogging depth and waterlogging duration were set for waterlogging treatment, and three levels of waterlogging depth were set, namely 1/4PH (PH: plant height), 2/4PH, and 3/4PH. The duration of waterlogging was set at two levels, 5 d and 7 d. The waterlogging stress test started at 08:00 on 1 August (3), 2019. The waterlogging test was carried out in a flooded pool of 5 m × 1.5 m × 1.5 m. The water in the flooded pool was static and clean well water and it was not changed for 7 days. According to the designed waterlogging depth of the test, the measuring bucket was placed on boards of different heights (the height of the wooden board could be adjusted by adjusting the length of the rope, if necessary) to meet the three different waterlogging depths set in the test. During the test period, the water depth of the flooded pool was observed at 08:00 every day, and if the water level decreased, an appropriate amount of water was added. In the case of rainy weather, the depth of the water layer of the flooded pool was to be observed several times a day, and timely drainage carried out to control the water level of the flooded pool, always meeting the requirements of the flooded test. After the end of waterlogging, the rice was moved outside the pond, and shallow water irrigation was used during the non-stress period. Except for waterlogging, the remaining agricultural technology measures were the same as local management. The specific test treatment is shown in Table 1, water level control is shown in Figure 1, and the test treatment picture is shown in Figure 2.

Table 1. Design of waterlogging test during jointing–booting stage.

Treatment	Waterlogging Depths (RWH)	Waterlogging Duration	Date of Treatment
T1	1/4PH(25%)	7 d	1 August–8 August
T2	2/4PH(50%)	7 d	1 August–8 August
T3	3/4PH(75%)	7 d	1 August–8 August
T4	1/4PH(25%)	5 d	3 August–8 August
T5	2/4PH(50%)	5 d	3 August–8 August
T6	3/4PH(75%)	5 d	3 August–8 August
CK	0–5 cm		

Note: PH: plant height. R_{WH}(%): ratio of waterlogging depth to plant height. The PH at the beginning of waterlogged stress was 94 cm.

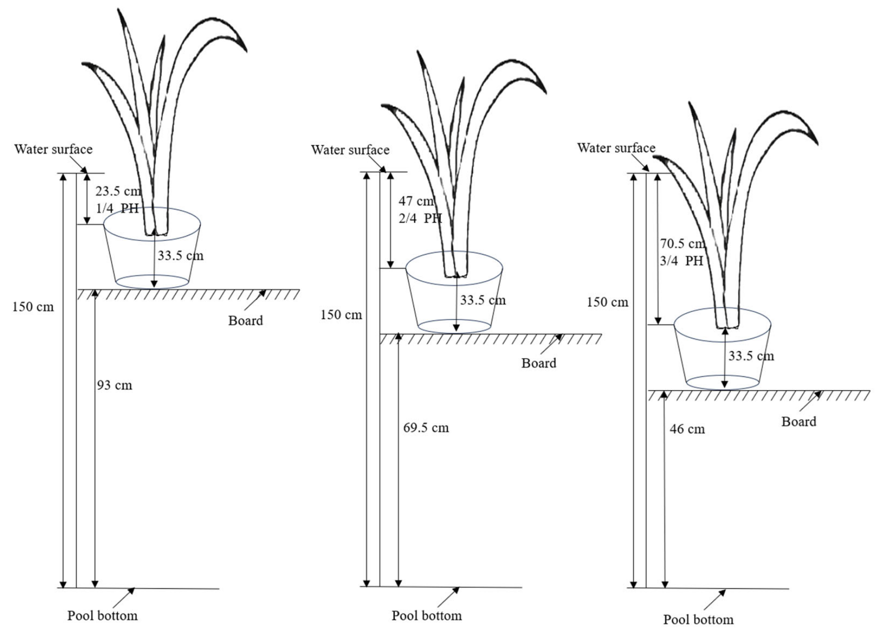
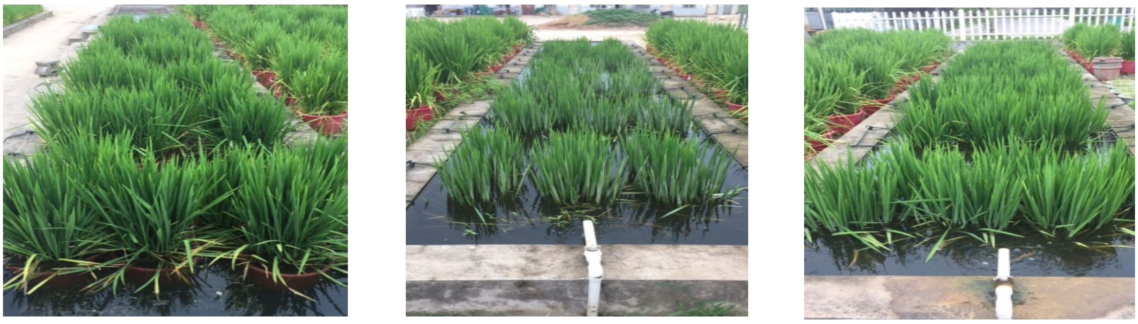


Figure 1. Water level control.



1/4 PH 2/4 PH 3/4 PH

Figure 2. Waterlogging stress test of rice at jointing–booting stage.

2.3. Test Items

Plant height: Before stress treatment (1 August), one rice plant was randomly selected from each pot for labeling, and six rice plants were randomly selected from each pot for labeling. After stress treatment (8 August), at the heading and flowering stage (28 August), grouting stage (10 September), and maturity stage (25 September), the height of labeling plants was measured with a steel ruler. The plant height before heading was the height from the ground surface to the highest leaf of each cluster, and the plant height after heading was the height from the ground surface to the highest spike top [23].

Leaf area: Leaf area was measured after waterlogging stress treatment at the jointing–booting stage, heading and flowering stage, and filling stage. Three representative plants with consistent growth were selected for each treatment, and leaf area was measured by a specific leaf mass method (dry sample weighing method). All the leaves in each pot were removed. Eighteen leaves were randomly selected, and six leaves were scanned three times each time using the WSeen LA-S plant image analyzer system (Hangzhou WSeen Detection Technology Co., Ltd., Hangzhou, China). The area of leaves was calculated as A_1, A_2, and A_3 The dry mass of the leaves with the known area and the remaining leaves was measured by the drying method, and the average specific leaf area K (g·cm^{-2}) was obtained; then, the leaf area of all leaves was converted. The calculation formula is as follows:

$$\mathrm{K} = \frac{\frac{m_1}{A_1} + \frac{m_2}{A_2} + \frac{m_3}{A_3}}{3} \tag{1}$$

$$A_{total} = \frac{m_1 + m_2 + m_3 + m_{residual}}{K} \tag{2}$$

where m_1, m_2, and m_3 are the dry mass (g) of small sample leaves corresponding to the scanned cubic leaf area (A_1, A_2, A_3), and $A_{\ total}$ is the total leaf area (cm^2); $m_{residual}$ is the dry mass (g) of the remaining leaves.

Above-ground dry matter weight: Samples were taken after the stress at the jointing–booting stage, and samples were taken once at the heading and flowering stage, grouting stage, and maturity stage after shallow water irrigation, with 3 replicates per treatment. The determination method [24] was as follows: the above-ground part of each pot plant was divided into leaves, stem sheath, and ear dry matter; the green was killed at 105 °C for 30 min and then dried at 80 °C to constant mass, and the dry matter mass of each part was measured with an electronic balance with a sensitivity of 0.01 g.

Test seed and yield: After rice ripening, five pots were taken from each treatment to test the yield. The main items of seed testing were panicle length, panicle weight, seed setting rate, and 1000-grain weight. Each pot was counted separately.

2.4. Analysis of Data

Microsoft Excel 2016 and SPSS 19.0 software were used to analyze the data, and Duncan's new complex range method was used to test the significance.

3. Results and Analysis

3.1. Effect of Waterlogging Stress on Plant Height of Rice

As can be seen from Figure 3, after the end of waterlogging stress at the jointing–booting stage (08/08), the plant height of all plants from high to low was as follows: T3 > T6 > T2 > T5 > T1 > T4 > CK. The plant height of all waterlogging stress treatment plants exceeded CK. Among them, the plant height of the T3 treatment (3/4PH, 7 d) was the greatest and had significantly increased by 31.90% compared with CK, and that of the T6 treatment (3/4PH, 5 d) came second and had significantly increased by 15.93% compared with CK. Compared to the T6 treatment, the T3 treatment significantly increased by 13.77%. The results showed that the waterlogging depth of 3/4PH during the jointing–booting stage and the longer the waterlogging duration, the more obvious the increase in plant height was. Compared with T2 and T1, the T3 treatment significantly increased by 14.37% and 19.06%, indicating that the longer the flooding duration, the more significant the increase in rice plant height. Waterlogging treatment at the jointing–booting stage can promote the growth of rice plant height.

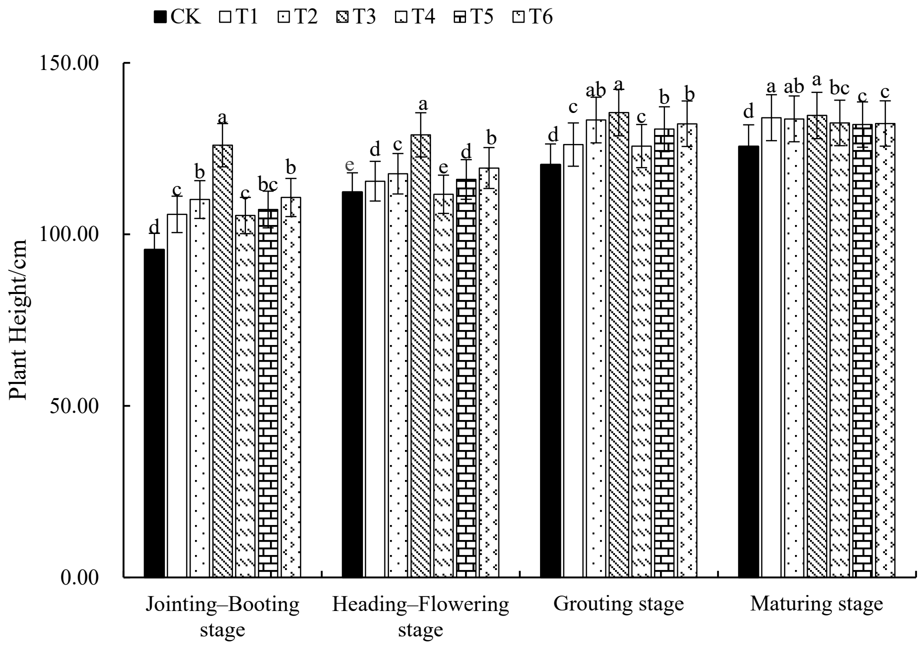


Figure 3. Changes in rice plant height under different waterlogging stress treatments. Note: Different low-ercase letters indicate significant differences between treatments ($p < 0.05$). Same as below.

After the end of the 20 days of waterlogging stress (heading and flowering stage, 28/08), the plant height of rice treated with waterlogging for 7 days was still significantly higher than that of CK, and the height of rice treated with T1, T2, and T3 had significantly increased by 2.82%, 4.75%, and 14.84% compared with CK, respectively. The plant height of rice under 5 days of waterlogging was greater than CK, and the heights of rice under the T5 and T6 treatments were 3.27% and 6.23% greater than CK, respectively. From the end of waterlogging stress to the filling stage (10 September), the plant height of all flooded treatments was still higher than that of CK, and the plant height of the T1, T2, and T3 treatments had significantly increased by 4.85%, 10.80%, and 12.60% compared with CK, respectively, and that of the T4, T5, and T6 treatments had significantly increased by 4.49%, 8.59%, and 9.90% compared with CK, respectively. From the end of waterlogging stress to maturity (25 September), the plant height of all rice treated with waterlogging stress exceeded CK, and the plant height of rice treated with waterlogging for 7 days exceeded that of rice treated with waterlogging for 5 days. The above data indicate that after the relief of waterlogging stress, the early waterlogging treatment has a certain after-effect on the later growth of rice plant height.

In conclusion, waterlogging treatment at the jointing–booting stage can promote the increase of rice plant height, In the same duration of waterlogging, the increase of plant height increased with the increase of waterlogging depth. At the same waterlogging depth, the increase of plant height increased with the increase of waterlogging duration.and had a certain after-effect on the growth of rice plant height in the later period.

3.2. Effects of Waterlogging Stress on the Population Leaf Area of Rice

As can be seen from Figure 4, after waterlogging treatment at the jointing–booting stage, the population leaf area treated with T1, T3, T4, and T5 was greater than that treated with CK, while that treated with T2 and T6 was smaller than that treated with CK, but the differences were not significant. When the stress was relieved at the heading and flowering stage (28 August), the leaf area of all stress treatments was lower than that of CK, and the T1, T2, T3, T4, T5, and T6 treatments significantly decreased by 20.89%, 14.79%, 18.40%, 40.70%, 18.26%, and 27.11% compared to CK, respectively. These results indicated that after the end of waterlogging stress at the jointing–booting stage and the return to normal growth conditions, the leaf area of the rice population would decrease somewhat, and the increase of the leaf area of the rice population would be inhibited by waterlogging and show a certain lag. When the stress was removed at the filling stage (10 September), the population leaf area of all flooded treatments was higher than CK, and the population leaf area of T3, T5, and T6 was higher than CK and had significantly increased by 53.10%, 44.48%, and 47.82% compared with CK. The results indicated that waterlogging treatment at the jointing and booting stage would increase the population leaf area of rice [25], promote the growth of rice leaves, and lead to the glutinousness and late ripening of rice in the later growth period, resulting in rice yield reduction.

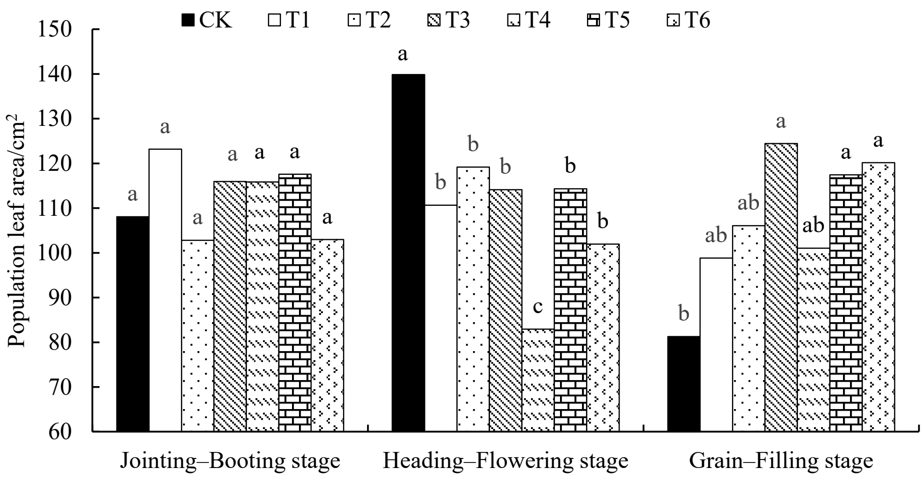


Figure 4. Effects of different waterlogging stress on the population leaf area of rice.

3.3. Effects of Waterlogging Stress on Dry Matter of Rice

3.3.1. Effects of Waterlogging Stress on Stem Weight

As shown in Figure 5, after waterlogging stress at the jointing–booting stage, the stem weight of rice treated with T2, T3, T4, T5, and T6 exceeded that of CK and had significantly increased by 12.10%, 27.75%, 26.14%, 20.80%, and 22.71% compared with CK, respectively, while that treated with T1 had significantly decreased by 12.50% compared with CK. These results indicated that waterlogging stress for 5 days at the jointing–booting stage could increase the stem weight of rice, but the T1 treatment could inhibit the increase in the stem weight of rice, which may be due to the insignificant increase in plant height (Figure 3). When the stress was relieved at the heading to flowering stages, the stem weight of rice treated with T5 was 23.55% lower than that of CK, and other treatments were close to CK. The stem weight of rice treated with T1, T3, and T6 was higher than CK and had significantly increased by 15.22%, 23.37%, and 25.08% compared with CK, respectively.

This was mainly due to the increase in plant height (Figure 3), indicating that waterlogging stress at the jointing–booting stage would promote the increase of plant height, showing a certain post-compensation effect, and thereby increase stem mass. The stem weight of rice treated with T1, T2, and T6 exceeded that of CK and had significantly increased by 49.32%, 23.56%, and 75.30% compared with CK, respectively. In conclusion, waterlogging for 7 days during the jointing–booting stage can increase the stem weight of rice, and waterlogging for 5 days when the depth of waterlogging exceeds half of the plant height can increase the stem weight of rice, which may be mainly due to the change of rice dry matter allocation coefficient by waterlogging treatment, which promotes the increase of rice plant height.

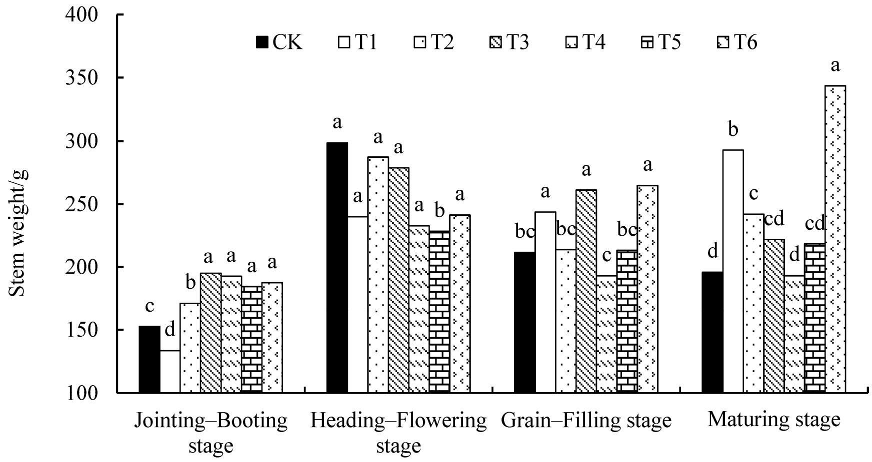


Figure 5. Effects of different waterlogging treatments on stem weight.

3.3.2. Effects of Waterlogging Stress on Leaf Dry Weight

It can be seen from Figure 6 that after flooding stress at the jointing–booting stage, the dry weight of rice leaves treated with T3 and T6 exceeded that of CK, and had significantly increased by 45.15% and 23.45% compared to CK. When the stress was relieved at the heading to flowering stages, the leaf dry weight of T3-treated rice was the greatest and had significantly increased by 33.50% compared to CK. The dry weight of rice leaves treated with T3 and T6 was greater than CK and had significantly increased by 42.94% and 23.59% compared to CK, respectively. When the stress was relieved at maturity, T3-treated rice dry leaf mass was the greatest, but there was no significant difference between T3 and CK. In conclusion, the T3 treatment at the jointing–booting stage can significantly increase the dry mass of rice leaves, and waterlogging at the jointing–booting stage can also increase the dry mass of rice leaves. The dry mass of rice leaves increased with the increase of waterlogging depth, while the duration of waterlogging was the same.

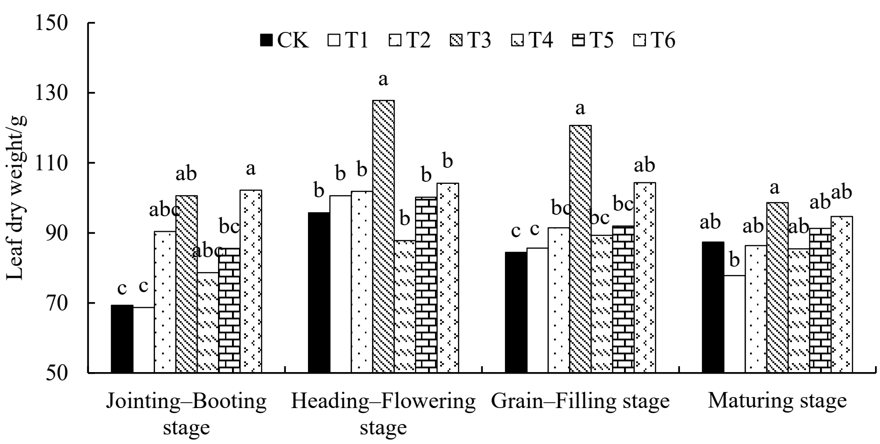


Figure 6. Effects of different waterlogging treatments on Leaf dry weight.

3.3.3. Effects of Waterlogging Stress on Above-Ground Dry Matter of Rice

As can be seen from Figure 7, after the end of waterlogging at the jointing–booting stage, the above-ground dry matter of rice treated with T2, T3, T4, T5, and T6 all exceeded CK, and those under the T2, T3, T4, T5, and T6 treatments had significantly increased by 17.83%, 33.18%, 22.20%, 21.62%, and 30.50% compared with CK, respectively. This was mainly due to the fact that waterlogging stress promoted the growth of rice stems and leaves (Figures 5 and 6). After 7 days of waterlogging, the above-ground dry matter mass increased with the increase of waterlogging depth. After stress relief at heading to flowering stages, the above-ground dry matter mass of rice treated 5 days after waterlogging was lower than that of CK, and those under T4, T5, and T6 treatments were significantly lower than CK by 23.97%, 25.05%, and 17.84%, respectively. When the stress was relieved at the grain filling stage, the above-ground dry matter mass of all waterlogging treatments was close to CK. When the stress was relieved at maturity, the above-ground dry matter of the T3 treatment was the lowest, which significantly decreased by 17.18% compared to CK. In conclusion, after waterlogging treatment at the jointing–booting stage, above-ground accumulation of rice was promoted in a short time. However, at the later growth stage, only the T6-treated rice above-ground dry matter mass was higher than CK, which was mainly due to the increase of rice stem dry matter under waterlogging treatment. After 7 days of waterlogging, the above-ground dry matter decreased with the increase in waterlogging depth.

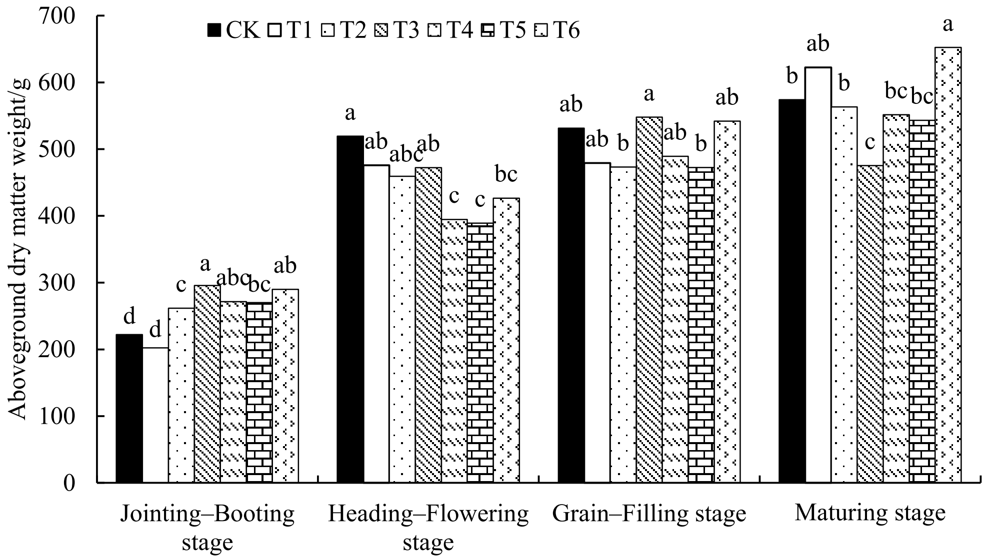


Figure 7. Effects of different waterlogging stress on aboveground dry matter weight.

3.3.4. Effects of Waterlogging Stress on Rice Yield

As can be seen from Table 2, after waterlogging stress at the jointing and booting stage, the ear length and ear weight of rice were lower than those of CK; especially in the T3 treatment, where ear length was significantly reduced by 21.34%, and ear weight was significantly reduced by 40.18% compared with CK. In all treatments (T1, T2, and T3), after 7 days of waterlogging, the panicle length and panicle weight of rice decreased with the increase of waterlogging depth. The 1000-grain weight of all stress treatments was lower than that of CK, and those under T2, T3, and T6 treatments significantly decreased by 10.12%, 18.29%, and 9.75% compared to CK, respectively. At the same waterlogging depth, the 1000-grains weight decreased with the increase of waterlogging days. In the same duration of waterlogging, the 1000 grains weight decreased with the increase of waterlogging depth. The seed setting rate of the T2 treatment was the lowest, which was significantly reduced by 16.38% compared to CK. The rice yield of all waterlogging treatments was lower than that of CK; especially that of 7 d waterlogging treatment was significantly lower than that of CK, and that of the T1, T2, and T3 treatments was significantly lower than that of CK by 14.50%, 26.50%, and 31.68%, respectively. After 7 d waterlogging, the rice yield decreased with the increase in waterlogging depth. It can be seen from the above analysis that with the same waterlogging duration, the 1000-grain weight and yield decreased with the increase in waterlogging depth, and with the same waterlogging depth, the 1000-grain weight and yield decreased with the increase in waterlogging duration.

Table 2. Effects of different waterlogging treatments on yield components during jointing–booting stage.

Treatment	Panicle Length (cm)	Panicle Weight (g)	1000-Grain Weight (g)	Seed Setting Rate (%)	Yield (g·pot^{-1})
T1	25.83 ab	3.57 ab	20.99 ab	74.23 ab	164.71 bc
T2	24.05 bc	3.21 ab	19.87 b	60.59 c	141.60 cd
T3	22.30 c	2.45 b	18.07 c	71.08 b	131.61 d
T4	25.78 ab	3.27 ab	21.45 a	77.49 ab	178.11 ab
T5	24.99 b	3.90 a	20.84 ab	75.44 ab	174.82 ab
T6	26.37 ab	3.87 a	19.96 b	81.66 a	169.17 ab
CK	28.35 a	4.10 a	22.11 a	72.46 ab	192.64 a

Note: Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

3.4. Regression Model of Rice Yield Reduction and Relative Waterlogging Depth

Based on the data of the pot experiment, SPSS 19.0 software was used to analyze the data, and a regression model of rice yield reduction rate and relative waterlogging depth (the ratio of water depth to plant height) was constructed. In this paper, the ratio of waterlogging depth to rice plant height is defined as R_{WH} (%), and the calculation method of yield reduction is as follows:

$$\text{Ratio of yield reduction } (\%),\ Y = \frac{\overline{Y}_{CK} - \overline{Y}_T}{\overline{Y}_{CK}} \times 100\% \quad (3)$$

where Y is the rice yield reduction (%), $\overline{Y}_{CK}$ is the average yield of the CK treatment test (g Pot^{-1}), and $\overline{Y}_T$ is the average yield of the waterlogging stress treatment test (g·Pot^{-1}). The regression equation of the ratio of rice yield reduction rate (Y) and the ratio of waterlogging depth to plant height (R_{WH}) is shown in Table 3.

Table 3. Relationship between Y and RWH under waterlogging stress at jointing–booting stage.

Duration of Waterlogging/d	Regression Relation	Correlation Coefficient (R^2)
7	y = 0.344x + 7.0333	0.9505
5	y = 0.0928x + 5.0167	0.9775

As can be seen from Table 3, when waterlogging lasted for 7 days, the ratio of waterlogging depth to plant height increased by 10, and the rice yield reduction rate increased by 3.4%; when waterlogging lasted for 5 days, the ratio of waterlogging depth to plant height increased by 10, and the rice yield reduction rate increased by 0.9%. When the depth of waterlogging is the same, the longer the duration of waterlogging, the more serious the yield reduction. If 20% of the rice yield reduction rate is taken as the drainage index, the ratio of waterlogging depth to the plant height of rice should not exceed 37% when the waterlogging duration of rice is 7 days.

4. Discussion

The jointing–booting stage of rice is a period when vegetative and reproductive growth go hand in hand, and it is also a period more sensitive to water. According to the analysis of rice growth indexes, the plant height of all the rice treated with flooding stress was higher than that of the control after the end of flooding at the joint period booting stage ($p < 0.05$), and the plant height of all the rice treated with flooding stress was still significantly higher than that of the control after normal irrigation to mature stage This is consistent with Shao Guangcheng's research results [26,27]. A large number of previous studies have shown that waterlogging treatment can promote the growth of rice, mainly because in order for the plant to adapt to waterlogging in a waterlogging environment, the secretion of more ethylene and gibberellin in rice plants will be stimulated. This, in turn, will stimulate the division and elongation of cells and further promote the elongation and growth of leaf sheath, leaves, and stem segments, thus raising the top of the plant above the water [21,22,28]. This ensures contact with air to maintain respiration [29] and secure normal photo cooperation to obtain organic carbon, thus ensuring overall rice yield [12,15]. There was no significant difference in leaf area among all treatment groups after flooding at the jointing–booting stage, but from normal irrigation to the grouting stage, the leaf area of all treatment groups was higher than that of control. At the end of the jointing–booting stage, water flooding at 2/4PH and 3/4PH depth increased dry matter in rice. It can be observed that moderate waterlogging stress positively influences rice growth and leaves lasting aftereffects. This may stem from the fact that flooding alters the dry matter allocation coefficient of rice organs, typically manifesting in an increased allocation of dry matter to leaves and stems. Consequently, this stimulates the growth of rice leaves, expands leaf area, and boosts above-ground dry matter accumulation in rice, while reducing the dry matter allocation to panicles [30]. This could be attributed to rice being a water-tolerant plant.

Our study reveals that waterlogging during the jointing–booting phase augments the dry matter mass of rice stems and leaves, owing to shifts in organ allocation coefficients. This amplified dry mass necessitates carbon assimilation, ultimately diminishing rice yield. Waterlogging stress impacts rice yield and its component factors, with varying effects depending on the growth stage, depth, and duration of the waterlogging. The results of this experiment showed that waterlogging stress at the jointing–booting stage could reduce panicle length, panicle weight, 1000-grain weight, and seed setting rate of rice, especially under the T3 treatment, and the dry mass per panicle decreased with the increase in waterlogging depth, thus reducing rice yield [17], which was consistent with the results of Wang et al. [21]. Waterlogging during the jointing–booting stage can reduce rice yield, and waterlogging for 5 days has no significant effect on rice yield, while waterlogging for 7 days has a significantly lower effect than CK. The test results show that appropriate waterlogging during the jointing–booting stage has no significant effect on rice yield, but the impact on rice yield becomes more obvious with the increase in waterlogging duration. An analysis of the relationship between yield reduction (Y) in middle rice and the ratio of waterlogging depth to plant height (%) reveals that longer waterlogging durations during the jointing–booting stage, coupled with the same waterlogging depth, lead to more severe yield reductions [31]. Similarly, deeper and longer waterlogging results in more significant rice yield losses. This is primarily because the young panicle of rice gradually forms during the jointing period. When subjected to waterlogging stress, the differentiation of young panicles in rice is impeded, leading to a substantial decrease in yield [16].

Rice is prone to flooding at the jointing stage, and its occurrence period, intensity, and duration vary from place to place. At the same time, the response mechanism of rice to waterlogging stress is also closely related to the waterlogging tolerance of rice varieties. The waterlogging tolerance of different rice varieties is different, and the difference among different varieties is great. The results of this experiment are only a one-year experimental study, and the differences between different rice varieties have not been considered. In the future experimental research process, it is necessary to include the comparison between different rice varieties. Some studies have shown that the waterlogging tolerance of hybrid rice is stronger than that of conventional rice [32,33], and that of conventional indica rice is stronger than that of conventional japonica rice [34,35]. Therefore, a large number of experimental studies are needed to fully reveal the effect of waterlogging stress on rice yield at the jointing stage. The results showed that the ratio of waterlogging depth to plant height of rice should not exceed 37% when rice waterlogging lasted for 7 days. It can provide a scientific basis for the drainage management of rice fields during waterlog disasters.

5. Conclusions

Waterlogging treatment during the jointing–booting stage of rice growth can notably elevate plant height, subsequently augmenting the dry matter weight of the rice stem and, consequently, the overall dry matter of the rice plant above ground. This effect is particularly pronounced after a 7-day waterlogging treatment. At this crucial growth phase, the leaf area of the rice population initially expands, then contracts, and expands again. This fluctuation leads to delayed greening and ripening of the rice, ultimately resulting in diminished rice yields, especially when subjected to a 7-day waterlogging period. Additionally, waterlogging treatment can decrease both the weight of 1000 grains and the seed setting rate of rice, thereby reducing overall rice production. Notably, a 7-day waterlogging treatment significantly impacts rice yield negatively. However, experimental results indicate that a 5-day flooding period during the jointing–booting stage does not significantly affect rice yield compared to the control group. Hence, in the case of flooding during this stage, it is advisable to drain the field water within 5 days to minimize the adverse effects of waterlogging on rice production.

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