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The Effects of Paclobutrazol Seed Soaking on Biomass Production and Yield Formation in Direct-Seeded Rice

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Abstract: Direct-seeded rice has been widely adopted in Asia in recent years. However, its low and unstable yields severely limit the increase in rice production and directly affect food security. The aim of this research was to investigate the effects of different concentrations of paclobutrazol seed soaking on the biomass production and yield formation of direct-seeded rice and to find the optimal concentrations to provide a theoretical basis for the high-yielding cultivation of direct-seeded rice. Two rice varieties, Jiyujing and Jijing305, were used in this experiment, and the seeds were soaked in paclobutrazol at concentrations of 0, 50, 100, 150, and 200 mg L^{-1}. The appropriate concentration of paclobutrazol seed soaking increased the yield of direct-seeded rice; this was attributed to the increase in the spikelet per unit area and the seed setting rate. However, the too-high paclobutrazol concentration was not conducive to a yield increase. Regression analysis showed that the appropriate concentration of paclobutrazol seed soaking was 100–105 mg L^{-1}. The appropriate concentration of paclobutrazol for seed soaking ensured the seedling emergence rate; improved the seedling quality, stem tillers, and productive tillers; increased the efficient leaf area, chlorophyll content, and net photosynthetic rate, resulting in an increase in dry matter accumulation; coordinated the source-sink relationship and dry matter distribution; and promoted the material translocation from the "source" to the "sink". In conclusion, using the appropriate concentration of paclobutrazol for seed soaking is an effective means of obtaining high yields of direct-seeded rice.

Keywords: direct-seeded rice; paclobutrazol; biomass production; yield

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1. Introduction

Rice is a staple food for more than half of the world's population [1]. By 2050, the global population will exceed 9 billion, requiring an increase in food productivity of at least 70% to meet human food demands [2]. Therefore, increasing the yield per unit area of rice remains an urgent goal [3]. The improvement of agronomic practices to achieve high yields is the focus of agronomic research.

Transplanting and direct seeding are the two most widely used cultivation methods in rice crop production. Due to the economic development and adjustment of the structure of the agricultural industry in China, technology used for the direct-seeded cultivation of rice is valued for its low labor requirements and high efficiency [4–7]. Northeast China is an emerging rice production base, playing an increasing role in China's crop production and food security [8]. Northeast China has the advantages of excellent soil and cultivation conditions and a high degree of mechanization, which are highly favorable for the development of direct-seeded rice. However, the yields of direct-seeded rice may be lower than (or comparable to) those of transplanted rice [7,9]. This yield reduction is mainly attributed to the difficulty of obtaining all seedlings in 1 sowing in the field, as well as to plants with shallow roots, which are prone to lodging, and to the increase in panicle sterility [7,9].

Paclobutrazol is a low-dose, low-cost plant growth regulator used in agriculture to reduce lodging rates in crops [10,11]. In addition, paclobutrazol is known to have significant effects on crop stress resistance, such as reducing the damage caused by stresses such as drought, submergence, and salinity [12–14]. Paclobutrazol can be applied using conventional methods, including foliar spraying, soil drenching, and seed soaking [15]. Compared to other methods, seed soaking has the advantages of saving time and labor and allowing for accurate dosing, which is conducive to large-scale applications in agricultural production. The process of rice yield formation is actually the process of dry matter accumulation, distribution, and transport, and the accumulation of dry matter in rice directly affects the level of the rice yield [16]. Paclobutrazol application improves the quality of crop seedlings and increases the number of tillers, increases chlorophyll content and the net photosynthetic rate of the leaves and delays the rate of leaf senescence; it also increases dry matter accumulation, promotes the assimilation partitioning of seeds, and improves crop yields [17–20]. The present investigation of the effects of paclobutrazol on rice mostly focuses on the resistance to lodging. However, there is a lack of systematic research on the effects of paclobutrazol seed soaking on biomass production and yield formation in direct-seeded rice. Therefore, we assumed that paclobutrazol seed soaking could increase dry matter accumulation and improve the yield of direct-seeded rice. To verify our assumptions, a 2 year field study was conducted to investigate the effects of paclobutrazol seed soaking on yield and yield components, the seedling emergence rate, seedling quality, stem tiller dynamics, the efficient leaf area, chlorophyll content, the net photosynthetic rate, and dry matter accumulation, distribution, and translocation in direct-seeded rice. The aim of this research was to investigate the effects of different concentrations of paclobutrazol seed soaking on the biomass production and yield formation of direct-seeded rice and to identify the optimal concentrations as a theoretical basis for the high-yield cultivation of direct-seeded rice.

2. Materials and Methods

2.1. Experiment Site, Time, and Materials

The experiment was carried out in an experimental field at the National Crop Variety Validation and Characterization Station of Jilin Agricultural University, Changchun, Jilin Province (43°81′ N, 125°42′ E, 221 m altitude) in 2021–2022. Rice (*Oryza sativa* L.) varieties Jiyujing (JYJ) and Jijing305 (JJ305) were used in both years. The durations from sowing to the maturity of the 2 varieties were 135 days and 136 days, respectively. Before the experiment, the basic properties of the soil were: 16.86 g kg^{-1} organic carbon, 46.81 mg kg^{-1} alkaline hydrolysis (N), 29.72 mg kg^{-1} available phosphorus (P), 129.83 mg kg^{-1} available potassium (K), and a pH of 6.3.

2.2. Experimental Design

The experiment was a single-factor randomized zonal trial with a paclobutrazol seed soaking treatment. Prior to seed treatment with plant growth regulators, the rice seeds were sterilized with 5% sodium hypochlorite solution for 10 min and then rapidly washed several times with distilled water. The rice seeds were soaked in paclobutrazol at concentrations of 0 mg L^{-1} (CK), 50 mg L^{-1} (S1), 100 mg L^{-1} (S2), 150 mg L^{-1} (S3), and 200 mg L^{-1} (S4) for 24 h.

The plot size was 30 m^2 with 3 replicates. The rice was planted by direct seeding, the soil of the rice field was loosened and suppressed, and the seeds were sown by hand after harrowing and smoothing. The seeds were sown at the beginning of May with a hill spacing of 13.3 cm × 25 cm and a sowing rate of 80 kg ha^{-1}. The same N, P and K fertilizers were applied in all treatments at the recommended rates of 150 kg N (as urea), 75 kg P (as calcium superphosphate) and 75 kg K (as potassium chloride) ha^{-1}. For all treatments, N fertilizer was applied as basal (40%), early tillering topdressing (30%) and panicle initiation (PI) topdressing (30%); P fertilizer was only basally applied; and K fertilizer was applied as a basal (50%) and PI topdressing (50%). Water management mainly involved rain-feeding before the 4-leaf stage, with tensiometers installed in the plot to monitor the soil moisture conditions and to supplement irrigation if the soil conditions were too dry. When the seedlings reached the 4-leaf stage, flood irrigation management began until 1 week before harvest, a 3–5 cm floodwater depth of water was maintained throughout the field. Throughout the growing season, diseases, insects, and weeds were strictly controlled.

2.3. Sampling and Measurements

2.3.1. Seedling Emergence Rate

After neat emergence, the seedling emergence rate in a 1 m^2 area was investigated with 3 replications. The seedling emergence rate is calculated as follows:

$$\text{Seedling emergence rate (\%)} = \text{seedlings number}/\text{seeds number} \times 100\%.$$

2.3.2. Seedling Quality

At 30 days after sowing, 20 representative plants were selected in each treatment, and the roots were rinsed with clean water. After this, they were brought back to the laboratory to investigate the leaf age, seedling height, and stem base width. Each seedling was divided into 2 portions (shoot and root). They were placed in an oven at 105 °C for 30 min with subsequent oven-drying at 80 °C until constant weight to determine the dry weight of the shoots and roots. The root-shoot ratio, plumpness, and strong seedling index are calculated as follows [21]:

$$\begin{aligned}&\text{Root-shoot ratio} = \text{root dry weight}/\text{shoot dry weight};\\&\text{Plumpness } (\text{mg}\cdot\text{cm}^{-1}) = \text{shoot dry weight}/\text{seedling height};\\&\text{Strong seedling index} = \text{stem base width} \times \text{plumpness}.\end{aligned}$$

2.3.3. Tiller Dynamics

Twelve plants in each plot were sampled for the observation of tiller numbers at the mid-tillering, PI, heading stage (HD), and maturity stage (MA). The percentage of productive tillers was defined as the number of panicles as a percentage of the number of tillers observed at the PI.

2.3.4. Efficient Leaf Area

For the determination of efficient leaf (flag leaf, second leaves, and third leaves) area, 5 representative plants were selected from each plot at the HD, early filling stage (EF), mid-filling stage (MF), and late filling stage (LF), according to the average number of stem tillers. The efficient leaf area of the 5 representative plants was determined manually by measuring the leaf length and maximum leaf width (Leaf area = leaf length × maximum leaf width × 0.75).

2.3.5. Chlorophyll Content

Flag leaves were selected from each treatment at the HD, EF, MF, and LF. The leaf chlorophyll was extracted with ethanol and acetone at a ratio of 1:1. The leaves were weighed to 0.1 g, put into a test tube, added to the solvent or extracted and fixed to 10 mL; then, they were capped and extracted in a dark room at room temperature until the leaves turned white. The corresponding absorbance values were measured using a spectrophotometer at 645 nm and 663 nm, and the chlorophyll content was calculated using the formula as described by Arnon [22].

2.3.6. Net Photosynthetic Rate

The net photosynthetic rate was measured at the HD and MF. The photosynthetic rate of flag leaves was measured using a gas exchange analyzer (Li-Cor 6400 portable photosynthesis measurement system, Li-Cor, Lincoln, NE, USA). Measurements were taken from 09:00 to 11:00 h when photosynthetic-active radiation above the canopy was 1200 μmol m^{-2} s^{-1}. Six leaves were used for each treatment.

2.3.7. Dry Matter

Five representative plants were selected from each treatment at the HD, EF, MF, LF, and MA, according to the average number of tillers. The representative plants were divided into 3 portions, the stem sheath, leaf, and panicle; they were placed in an oven at 105 °C for 30 min with subsequent oven-drying at 80 °C until constant weight to determine the dry weight of the stem sheath, leaf, and panicle. The Dry matter translocation, dry matter translocation rate, and contribution rate of dry matter translocation to panicle are calculated as follows:

Dry matter translocation (t ha^{-1}) = dry matter weight of leaf (stem-sheath) at the HD − dry matter weight of leaf (stem-sheath) at the MA;

Dry matter translocation rate (%) = dry matter translocation/dry matter weight of leaf (stem-sheath) at the HD × 100%;

Contribution rate of dry matter translocation to panicle (%) = (leaf translocation + stem-sheath translocation)/(panicle dry matter weight at the MA − panicle dry matter weight at the HD) × 100%.

2.3.8. Yield and Yield Components

Nine representative plants from each plot were sampled at MA and brought back for investigation of the yield components; the spikelet per panicle, seed setting rate, and thousand-grain weight were calculated, as was the theoretical yield.

2.4. Data Analysis

Data obtained in this study were processed by SPSS 23.0 software. One-way analysis of variance (ANOVA) and Duncan's method for multiple comparisons were used to test the significant difference at the $p < 0.05$ level. All graphs were constructed with Origin 2021 and By Figdraw.

3. Results

3.1. Effects of Paclobutrazol Seed Soaking on the Seedling Emergence Rate and Seedling Quality in Direct-Seeded Rice

The seedling emergence rate of direct-seeded rice showed a trend of a gradual decrease with increasing paclobutrazol concentrations, and the lowest emergence rate was reached in the S4 treatment; the difference between the treatments was not significant (Table 1). Compared with the control, paclobutrazol seed soaking increased the leaf age, stem base width, root-shoot ratio, plumpness, and strong seedling index; it showed a trend of increasing and then decreasing with the increasing paclobutrazol concentration, reaching the maximum in the S2 treatment, and the difference was significant. Paclobutrazol seed soaking reduced the seedling height and showed a trend of gradual decrease with increasing paclobutrazol concentration, and the lowest seedling height was reached in the S4 treatment.

3.2. Effects of Paclobutrazol Seed Soaking on the Stem Tiller Dynamics in Direct-Seeded Rice

The stem tiller dynamics of the direct-seeded rice showed a trend of increasing and then decreasing (Figure 1). Compared with the control, the number of tillers of direct-seeded rice was increased by paclobutrazol seed soaking and showed a trend of increasing and then decreasing with increasing paclobutrazol concentration, reaching the maximum values in the S2 treatment. The productive tillers of direct-seeded rice were increased by paclobutrazol seed soaking and showed a trend of increasing and then decreasing with increasing paclobutrazol concentrations, reaching a maximum in the S2 treatment (Figure 2). Compared to the control, the productive tillers of JYJ and JJ305 under the conditions of paclobutrazol seed soaking were increased by 1.41–3.64% (2 year average) and 0.63–2.69% (2 year average), respectively.

Table 1. Effects of paclobutrazol seed soaking on the seedling emergence rate and seedling quality of direct-seeded rice.

Year	Cultivar	Treatment	Seedling Emergence Rate (%)	Leaf Age (Leaves)	Seeding Height (cm)	Stem Base Width (cm)	Root-Shoot Ratio	Plumpness (mg·cm^{-1})	Strong Seedling Index
2021	JYJ	CK	72.73 a	3.60 c	17.55 a	0.26 b	0.28 d	3.54 c	0.92 c
		S1	71.82 a	3.85 bc	16.63 ab	0.29 ab	0.34 bc	4.12 b	1.19 bc
		S2	70.91 a	4.30 a	15.81 bc	0.33 a	0.38 a	4.98 a	1.62 a
		S3	69.09 a	4.15 ab	15.14 cd	0.31 ab	0.36 ab	4.86 a	1.52 a
		S4	67.28 a	4.05 ab	14.22 d	0.30 ab	0.32 c	4.64 a	1.40 ab
	JJ305	CK	73.64 a	3.45 b	16.36 a	0.31 b	0.28 d	3.95 d	1.22 d
		S1	71.82 a	3.80 ab	15.43 ab	0.33 ab	0.35 b	4.63 c	1.52 c
		S2	70.00 a	4.05 a	14.56 bc	0.38 a	0.37 a	5.59 a	2.12 a
		S3	69.09 a	4.00 a	13.83 c	0.37 a	0.35 ab	5.53 a	2.03 ab
		S4	66.37 a	3.85 ab	13.49 c	0.36 ab	0.32 c	5.08 b	1.80 b
2022	JYJ	CK	74.55 a	3.95 b	19.27 a	0.27 b	0.29 c	3.63 c	0.97 c
		S1	73.64 a	4.20 ab	18.03 b	0.31 ab	0.35 ab	4.25 b	1.30 b
		S2	72.73 a	4.55 a	17.41 b	0.34 a	0.37 a	4.99 a	1.70 a
		S3	71.82 a	4.50 a	16.34 c	0.32 a	0.36 a	4.99 a	1.61 a
		S4	69.09 a	4.25 ab	15.32 d	0.31 ab	0.33 b	4.81 a	1.51 ab
	JJ305	CK	75.46 a	3.65 b	17.66 a	0.33 b	0.30 d	4.13 c	1.35 d
		S1	73.64 a	4.05 a	16.53 ab	0.36 ab	0.35 bc	4.83 b	1.72 c
		S2	71.82 a	4.30 a	15.76 b	0.40 a	0.37 a	5.71 a	2.24 a
		S3	70.91 a	4.20 a	15.33 bc	0.37 ab	0.36 ab	5.55 a	2.04 ab
		S4	68.19 a	4.10 a	14.39 c	0.36 ab	0.33 c	5.33 a	1.90 bc

Note: Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

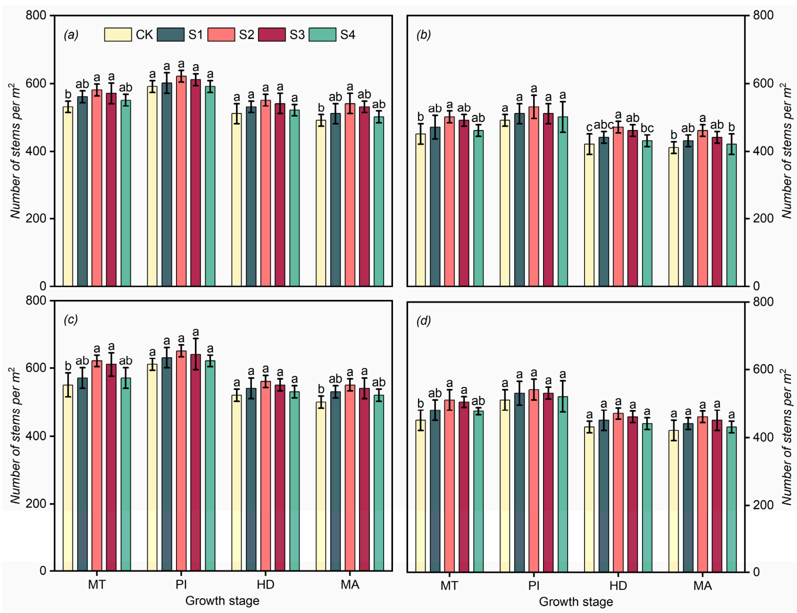

Figure 1. Effects of paclobutrazol seed soaking on the number of tillers of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; MT: mid tillering, PI: panicle initiation, HD: heading, MA: maturity; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol; Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

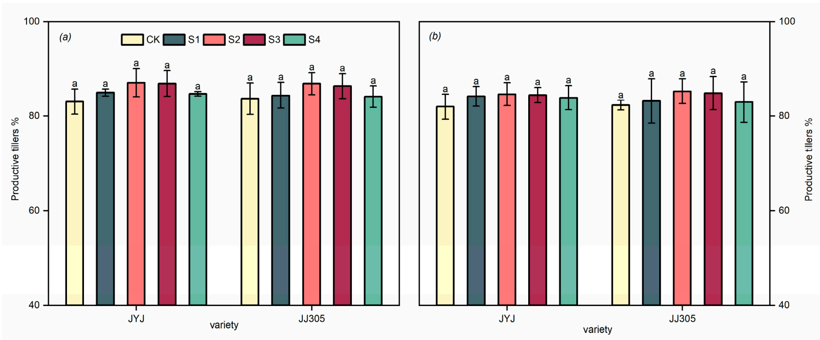

Figure 2. Effects of paclobutrazol seed soaking on the productive tillers of direct-seeded rice JYJ and JJ305 in 2021 (**a**) and 2022 (**b**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; JYJ: Jiyujing, JJ305: Jijing305; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol; Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

3.3. Effects of Paclobutrazol Seed Soaking on the Efficient Leaf Area in Direct-Seeded Rice

The efficient leaf area of direct-seeded rice tended to decrease gradually with the advancement of the reproductive period and reached the minimum during the LF (Figure 3). Compared with the control, paclobutrazol seed soaking increased the efficient leaf area of direct-seeded rice and showed a trend of increasing and then decreasing with the increase in the paclobutrazol concentration; it reached the maximum in the S2 treatment, and the difference was significant.

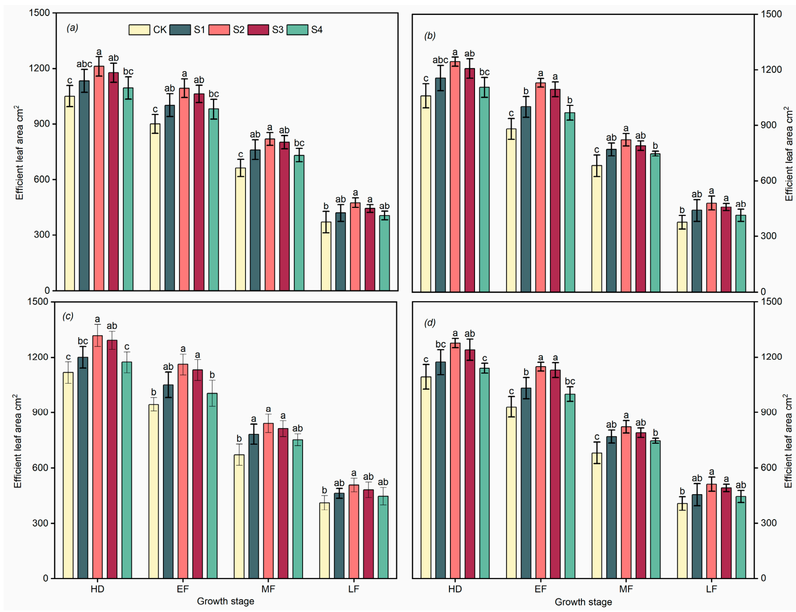

Figure 3. Effects of paclobutrazol seed soaking on the efficient leaf area of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; HD: heading, EF: early filling, MF: mid filling, LF: late filling; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol; Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

3.4. Effects of Paclobutrazol Seed Soaking on Chlorophyll Content in Direct-Seeded Rice

The chlorophyll content of direct-seeded rice tended to decrease gradually with the advancement of the reproductive period and reached the minimum at the LF (Figure 4). Compared with the control, paclobutrazol seed soaking increased leaf chlorophyll a, chlorophyll b, and the total chlorophyll content of direct-seeded rice; it showed a trend of increasing and then decreasing with the increase in the paclobutrazol concentration, reaching the maximum values in the S2 treatment, and the difference was significant.

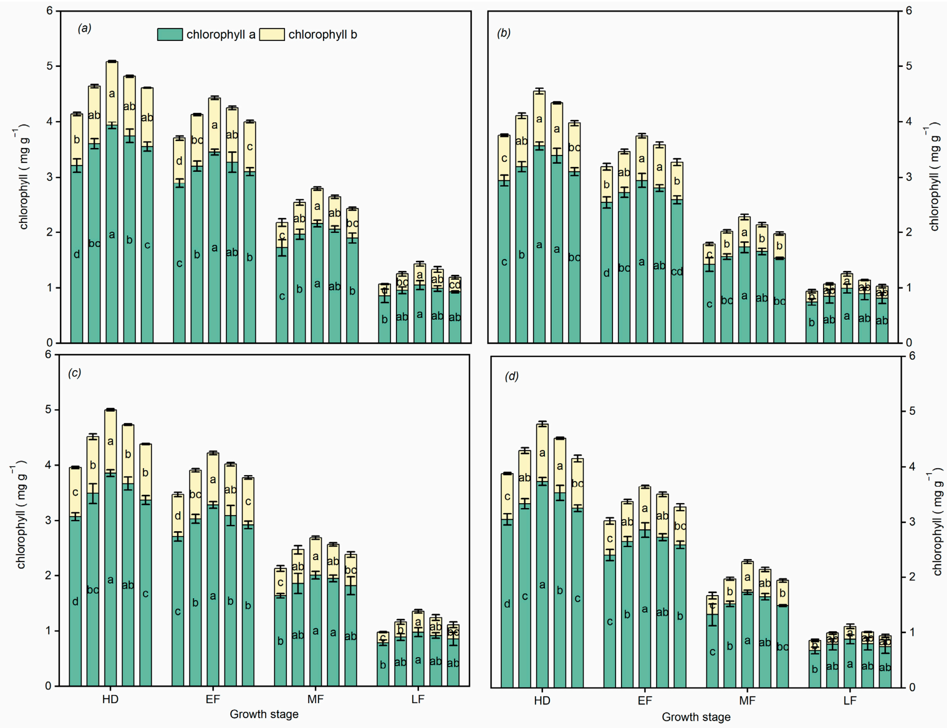

Figure 4. Effects of paclobutrazol seed soaking on chlorophyll content of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; HD: heading, EF: early filling, MF: mid filling, LF: late filling; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol; Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

3.5. Effects of Paclobutrazol Seed Soaking on Net Photosynthetic Rate in Direct-Seeded Rice

Compared with the control, paclobutrazol seed soaking increased the net photosynthetic rate of direct-seeded rice and showed a trend of increasing and then decreasing with the increase in the paclobutrazol concentration; it reached their maximum in the S2 treatment, and the difference was significant (Figure 5).

3.6. Effects of Paclobutrazol Seed Soaking on Dry Matter Accumulation, Distribution, and Translocation in the Direct-Seeded Rice

The dry matter accumulation in the leaves of direct-seeded rice tended to decrease gradually with the advancement of the reproductive period and reached the minimum in the MA; the dry matter accumulation in the stem sheath of direct-seeded rice tended to increase, then decrease and increase with the advancement of the reproductive period (Figure 6). It reached its maximum at the EF. The dry matter accumulation in the panicle of direct-seeded rice tended to increase gradually with the advancement of the reproductive period and reached its maximum in the MA. Compared with the control, the accumulation of dry matter in the leaves, stem sheath, and panicle was increased and showed a trend of increasing and then decreasing as the concentration of paclobutrazol increased; it reached the maximum value in the S2 treatment.

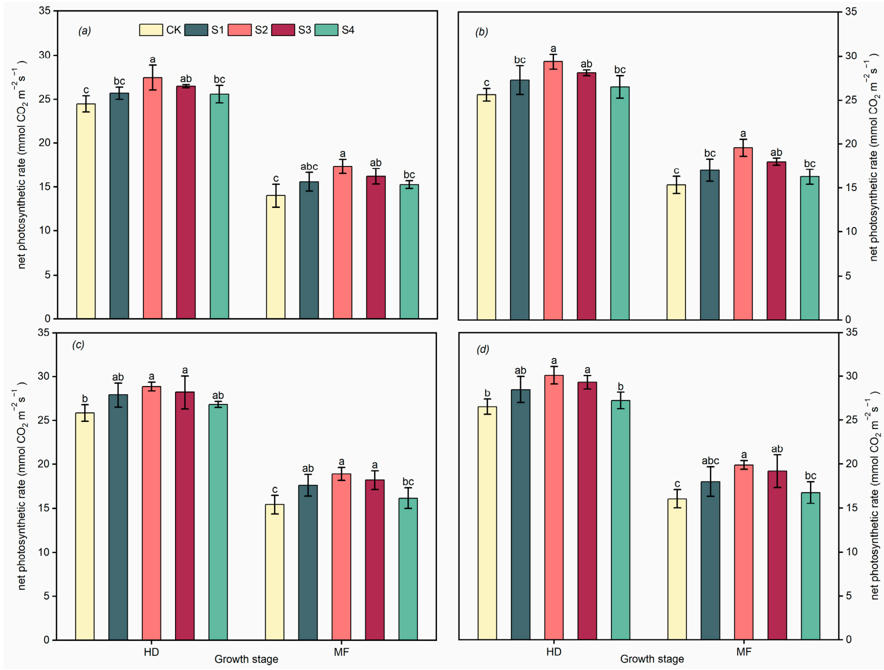

Figure 5. Effects of paclobutrazol seed soaking on the net photosynthetic rate of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; HD: heading, MF: mid filling; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol; Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

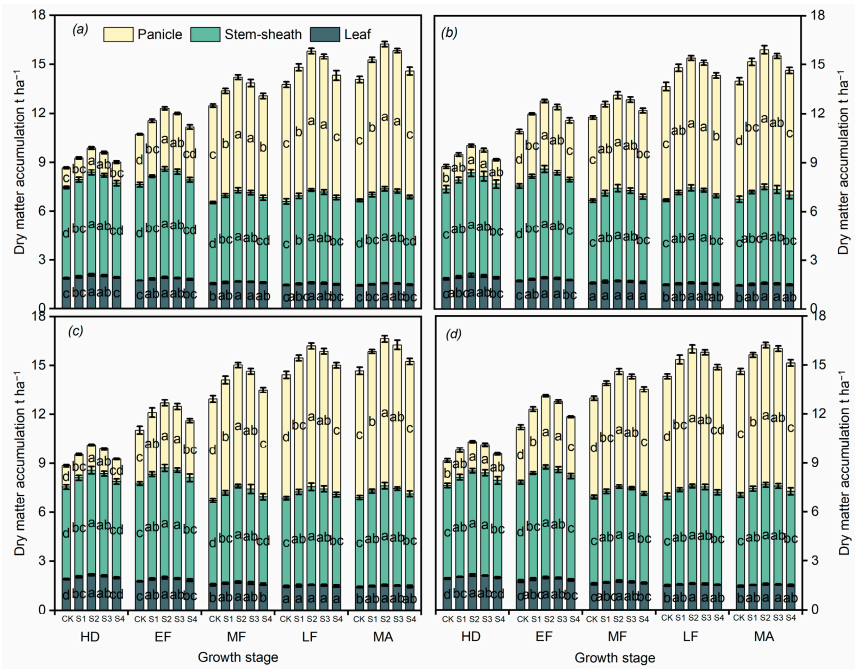

Figure 6. Effects of paclobutrazol seed soaking on dry matter accumulation of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; HD: heading, EF: early filling, MF: mid filling, LF: late filling, MA: maturity; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol. Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

The proportion of dry matter distributed in leaves and stem sheaths gradually decreased with the advancement of the reproductive period; it reached the lowest point in the MA, but the proportion of dry matter distributed in the panicle gradually increased and reached its highest point during the MA (Figure 7). Compared with the control, the distribution ratio of dry matter in the panicle was increased, but the distribution ratio of dry matter in the leaves and stem sheath was decreased under paclobutrazol seed soaking.

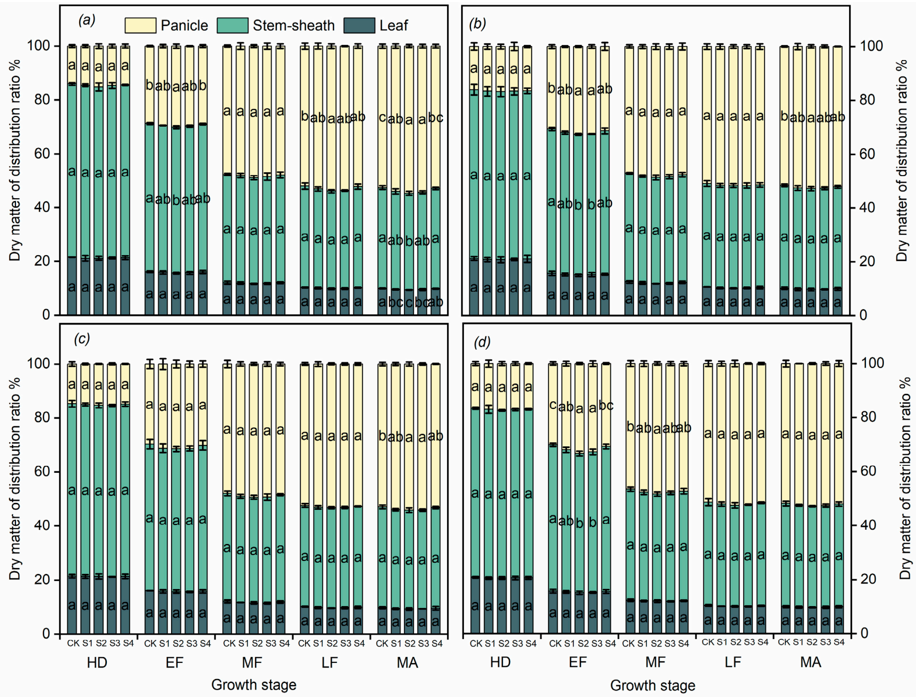

Figure 7. Effects of paclobutrazol seed soaking on dry matter distributed of direct-seeded rice JYJ (**a**,**c**) and JJ305 (**b**,**d**) in 2021 (**a**,**b**) and 2022 (**c**,**d**). CK: 0 mg L^{-1}, S1: 50 mg L^{-1}, S2: 100 mg L^{-1}, S3: 150 mg L^{-1}, S4: 200 mg L^{-1}; HD: heading, EF: early filling, MF: mid filling, LF: late filling, MA: maturity; Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol. Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

The translocation and translocation rate of the stem sheaths and leaves of direct-seeded rice from the HD to MA were increased and showed a trend of increasing and then decreasing as the concentration of paclobutrazol increased, reaching the maximum for the S2 treatment (Table 2). Meanwhile, the contribution of dry matter translocation to panicle increased and showed a trend of increasing and then decreasing as the concentration of paclobutrazol increased, reaching its maximum in the S2 treatment.

3.7. Effects of Paclobutrazol Seed Soaking on Yield and Yield Components in Direct-Seeded Rice

Paclobutrazol seed soaking increased the yield of direct-seeded rice and showed a trend of increasing and then decreasing with the increase in the paclobutrazol concentration. Both varieties reached their maximum in the S2 treatment, and the difference was significant (Figure 8). Compared to the control, the yields of JYJ and JJ305 under paclobutrazol seed soaking were increased by 1.85–17.04% (2 year average) and 1.50–16.25% (2 year average), respectively.

Table 2. Effects of paclobutrazol seed soaking on dry matter translocation of direct-seeded rice JYJ and JJ305 in 2021 and 2022.

Year	Cultivar	Treatment	Leaf		Stem-Sheath		Contribution Rate of Dry Matter Translocation to Panicle (%)
			Translocation ($t\ ha^{-1}$)	Translocation Rate (%)	Translocation ($t\ ha^{-1}$)	Translocation Rate (%)	
2021	JYJ	CK	0.46 b	24.34 a	0.32 c	5.46 c	12.58 a
		S1	0.48 ab	24.69 a	0.41 b	6.56 ab	12.98 a
		S2	0.54 a	25.89 a	0.48 a	7.16 a	13.74 a
		S3	0.52 ab	25.54 a	0.44 ab	6.80 ab	13.40 a
		S4	0.47 ab	24.42 a	0.37 c	5.99 bc	13.05 a
	JJ305	CK	0.43 a	22.97 a	0.17 c	3.02 a	10.41 c
		S1	0.47 a	23.77 a	0.25 abc	4.00 a	11.29 abc
		S2	0.52 a	25.00 a	0.32 a	4.77 a	12.46 a
		S3	0.51 a	24.82 a	0.28 ab	4.34 a	11.97 ab
		S4	0.46 a	24.00 a	0.20 bc	3.27 a	10.86 bc
2022	JYJ	CK	0.48 d	25.35 b	0.16 b	2.86 b	9.99 c
		S1	0.56 bc	27.78 a	0.24 ab	3.92 ab	11.32 abc
		S2	0.63 a	29.28 a	0.32 a	4.99 a	12.86 a
		S3	0.59 ab	28.27 a	0.32 a	5.03 a	12.48 ab
		S4	0.53 cd	27.00 ab	0.22 ab	3.70 ab	11.18 bc
	JJ305	CK	0.46 c	23.96 c	0.13 c	2.08 c	9.65 c
		S1	0.50 b	24.63 abc	0.21 b	3.22 b	10.80 b
		S2	0.55 a	26.06 a	0.30 a	4.43 a	12.60 a
		S3	0.54 a	25.74 ab	0.27 a	4.02 a	12.03 a
		S4	0.48 bc	24.23 bc	0.20 b	3.16 b	10.86 b

Note: Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

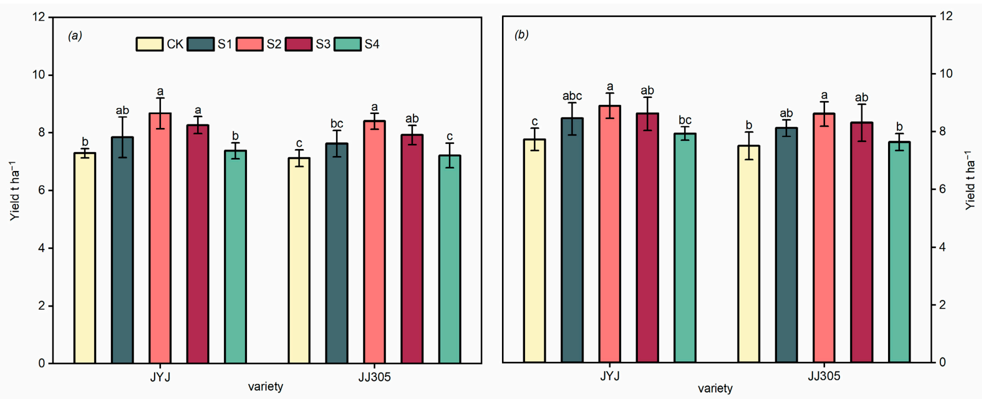

Figure 8. Effects of paclobutrazol seed soaking on the yield of direct-seeded rice JYJ and JJ305 in 2021 (**a**) and 2022 (**b**). Vertical bars represent ± sd. (n = 3) where these exceed the size of the symbol. Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences ($p < 0.05$).

Regression analysis was performed for the yields of direct-seeded rice and the five concentrations of paclobutrazol seed soaking (Figure 9). The quadratic equations for JYJ and JJ305 were $y = -1.09 \times 10^{-4}X^2 + 0.02X + 7.44$ and $y = -9.96 \times 10^{-5}X^2 + 0.02X + 7.26$, and the optimal concentrations (X) were 105.34 mg L^{-1} and 104.68 mg L^{-1}. Therefore, the optimal concentration of paclobutrazol seed soaking suitable for the formation of a high yield of direct-seeded rice was 100–105 mg L^{-1}; when the concentration of paclobutrazol seed soaking was greater than 105 mg L^{-1}, the yield showed a decreasing trend.

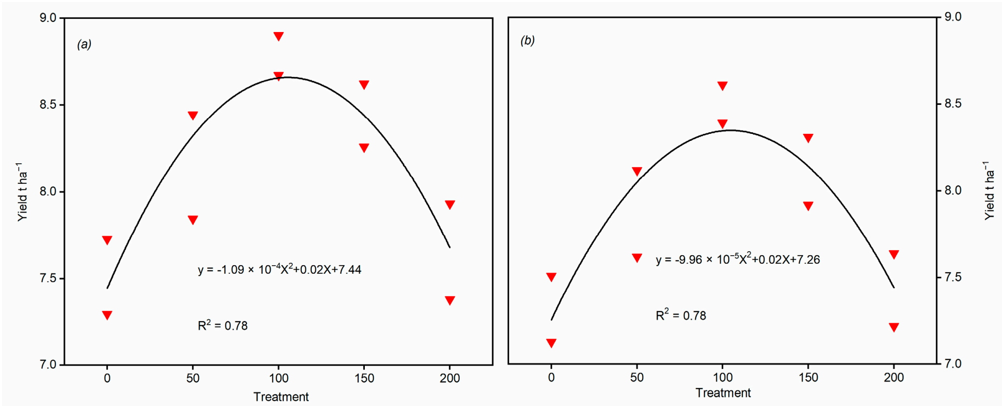

Figure 9. Regression analysis of different concentrations of paclobutrazol seed soaking and the yield of direct-seeded rice of JYJ (**a**) and JJ305 (**b**).

Compared with the control, the panicles, the spikelet per panicle, the spikelet per unit area, and the seed setting rate of direct-seeded rice were increased by paclobutrazol seed soaking; they showed a trend of increasing and then decreasing with the increase in the paclobutrazol concentration, reaching the maximum in the S2 treatment (Figure 10). Compared with the control, paclobutrazol seed soaking reduced the thousand-grain weight of direct-seeded rice, with both varieties reaching their minimum values in the S4 treatment, and the difference was significant.

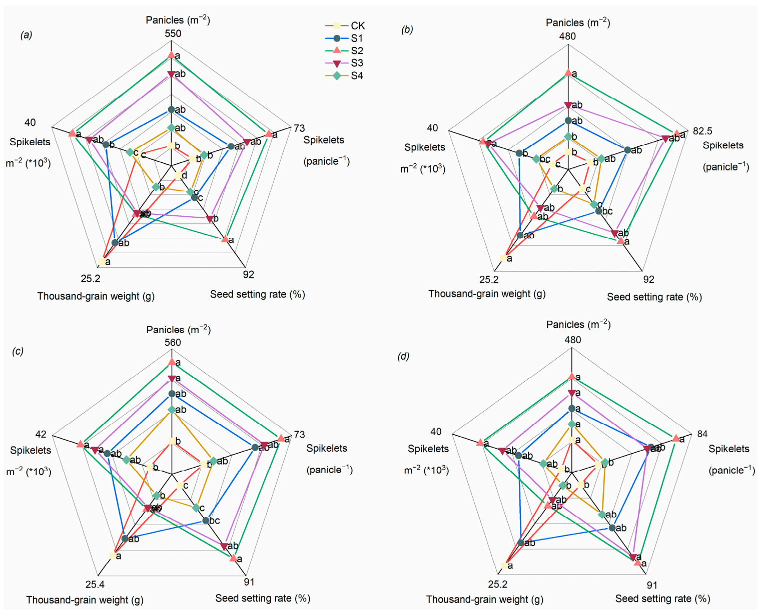

Figure 10. Effects of paclobutrazol seed soaking on the yield and yield components of direct-seeded rice JYJ (**a**,**b**) and JJ305 (**c**,**d**) in 2021 (**a**,**c**) and 2022 (**b**,**d**). Different lowercase letters in the figure indicate that different treatments of the same variety have significant differences (p < 0.05).

The correlation between yield and the spikelet per unit area was highly significantly positive, as was the correlation between the yield and the seed setting rate; meanwhile, the correlation between the yield and the thousand-grain weight was negative but not significantly so; the correlation between the thousand-grain weight and the spikelet per unit area was negative but not significant (Figure 11). The correlation between the accumulation of dry matter at the HD and the spikelet per panicle was highly significantly positive (Figure 12). The correlation between the accumulation of dry matter after the HD and the yield was highly significantly positive (Table 3).

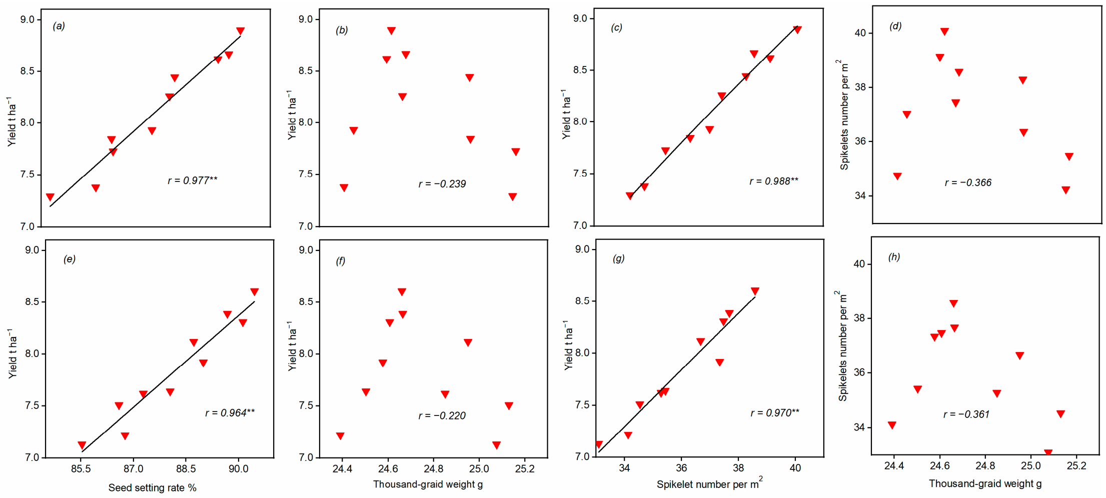

Figure 11. Correlation analysis of the spikelet per unit area, the seed setting rate and the thousand-grain weight with yield and the spikelet per unit area with the thousand-grain weight in direct-seeded rice of JYJ (**a**–**d**) and JJ305 (**e**–**h**). Correlation coefficients (r) are presented, and ** indicates significance at the 0.01 probability level.

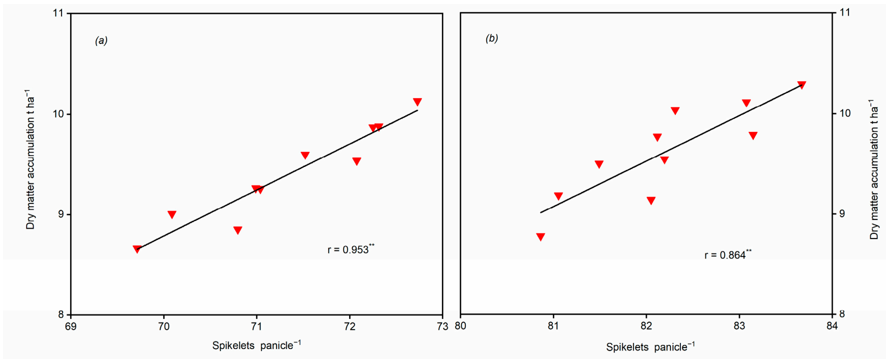

Figure 12. Correlation analysis of dry matter accumulation in the heading stage with the spikelet panicle^{-1} in the direct-seeded rice of JYJ (**a**) and JJ305 (**b**). Correlation coefficients (r) are presented, and ** indicates significance at the 0.01 probability level.

Table 3. Correlation analysis of dry matter accumulation of direct-seeded rice with the yield.

		Dry Matter Accumulation				
		HD	**EF**	**MF**	**LF**	**MA**
Yield	JYJ	0.965 **	0.976 **	0.965 **	0.982 **	0.983 **
	JJ305	0.968 **	0.947 **	0.945 **	0.960 **	0.965 **

Note: ** indicates significance at the 0.01 probability level.

4. Discussion

The seedling emergence rate and seedling quality are important factors affecting the high and stable yields of direct-seeded rice, which directly affect the population growth of rice plants [23,24]. Previous studies have shown that paclobutrazol could be used to improve seedling quality, increase seedling survival, promote rice seedling growth, and increase crop yields [25,26]. In this study, the appropriate concentration of paclobutrazol seed soaking ensured the seedling emergence rate of direct-seeded rice; however, the too high paclobutrazol concentration was not conducive to it (Table 1). The appropriate concentration of paclobutrazol seed soaking increased the leaf age, the stem base width, the root-shoot ratio, plumpness and the strong seedling index; additionally, it reduced the seedling height (Table 1). High seedling quality is conducive to improving the number of stem tillers and increasing the number of panicles, which, in turn, improves the rice yield [27]. As one of the factors most closely related to yield, the number of panicles per unit area is mainly determined during the nutritional growth period, when the number of tillers plays a decisive role in the final number of panicles [28]. Previous studies have shown that controlling the occurrence of ineffective tillers and increasing the productive tillers is an effective way to form high-quality rice populations [29,30]. In this study, paclobutrazol seed soaking increased the number of tillers and improved the productive tillers of direct-seeded rice, resulting in an increase in the number of panicles in direct-seeded rice (Figures 1, 2 and 10). This may be because paclobutrazol seed soaking improves seedling quality and promotes early rice tillering while effectively controlling ineffective tillering, resulting in an increase in the number of panicles in direct-seeded rice.

After the heading stage, the upper three leaves of rice, known as the efficient leaves, are the rice's main photosynthetic organ and the main source of assimilates needed for seed filling [31]. In this study, paclobutrazol seed soaking increased the efficient leaf area of direct-seeded rice (Figure 3), which ensured better light uptake and carbon assimilation in the upper three leaves, providing a sufficient material basis for grain filling. As the primary photosynthetic pigment in leaves, chlorophyll promotes photosynthesis through the efficient use of solar energy, thereby promoting plant growth and development [32]. It has been shown that plant growth regulators, especially triazole plant growth regulators, could enhance chlorophyll synthesis and delay leaf senescence in plants [33,34]. In this study, paclobutrazol seed soaking increased the chlorophyll a, chlorophyll b, and total chlorophyll content of leaves (Figure 4), which could be attributed to the ability of paclobutrazol treatment to increase cytokinin content and thus enhance chlorophyll biosynthesis [35]. Meanwhile, in this study, paclobutrazol seed soaking increased the net photosynthetic rate of leaves; the increase in the net photosynthetic rate could be caused by the increase in chlorophyll content (Figures 4 and 5). After heading, the rice gradually matures, and the physiological function of the functional leaves gradually declines; however, overly fast aging will inevitably affect photosynthesis and other physiological and biochemical reactions, which is not conducive to grain filling, resulting in a decline in the yield. Luo et al. showed that, during the filling period, photosynthesis has an important effect on the yield formation of rice [36]. Duan et al. showed that delaying leaf senescence at the filling stage is an effective method for improving rice yields [37]. In this study, compared with the control, paclobutrazol seed soaking increased chlorophyll content, the net photosynthetic rate, and the efficient leaf area in direct-seeded rice at the filling stage (Figures 3–5) so that the direct-seeded rice still maintained a high photosynthetic capacity. The higher chlorophyll content of leaves exposed to paclobutrazol seed soaking in the MF and LF also indicates that paclobutrazol seed soaking could delay leaf senescence to some extent (Figure 4).

Yield is the product of the harvest index and biomass accumulation at maturity, and improvements in yields must be predicated on increasing the biological yield. On the basis of a stable harvest index, further improvement of biomass accumulation at maturity is the key to further increasing rice yields [38,39]. In particular, the accumulation of biomass from the heading stage to maturity is essential for high biomass accumulation at maturity [40]. In this study, the accumulation of dry matter in the upper part of the ground of direct-seeded rice was increased by paclobutrazol seed soaking (Figure 6); the possible reason for this is that paclobutrazol seed soaking increased the net photosynthetic rate, chlorophyll content, and efficient leaf area of direct-seeded rice, as well as delaying leaf senescence, improving the photosynthetic production capacity of direct-seeded rice, and facilitating the accumulation of organic matter, resulting in the increased accumulation of dry matter in direct-seeded rice (Figures 3–5). The yield of direct-seeded rice was highly significantly and positively correlated with the accumulation of dry matter during the HD to MA (Table 3). During the filling period, non-structural carbohydrates that were stored in the stem sheaths pre-anthesis could be transported to the spikelet during grain filling, thus reducing the stem sheaths of the stalk's fullness [41]. In this study, paclobutrazol seed soaking increased the accumulation of dry matter in the stem sheath of direct-seeded rice during the filling stage (Figure 6), which was conducive to improving the resistance to overturning and thus increasing the yield of direct-seeded rice. In addition, paclobutrazol could regulate the "source-sink" balance of plants by altering the balance of endogenous hormones and redistributing nutrients [42,43]. Increasing the dry matter accumulation and distributing dry matter into the grain as much as possible is the most effective way to increase crop yield [44]. In this study, paclobutrazol seed soaking increased the proportion of dry matter distributed in panicles but decreased the proportion of dry matter distributed in the leaves and stem sheaths (Figure 7). The possible reason for this is that the paclobutrazol treatment promotes the translocation of organic matter underground as well as into the panicle, and the translocation of organic matter underground allows the crop to form a strong root system, which promotes the uptake and utilization of soil nutrients and water and facilitates crop growth [10]. Improving the contribution of post-anthesis dry matter to grain can increase grain yield [45,46]. In this study, paclobutrazol seed soaking increased the translocation and translocation rate in the leaves and stem sheaths of direct-seeded rice and the contribution rate of dry matter translocation to panicle (Table 2). One possible reason for this is that paclobutrazol seed soaking increases the reservoir capacity of direct-seeded rice, leading to more translocation from the nutrient organs to the spikelet (Figure 10). It can be concluded that delaying leaf senescence after flowering in direct-seeded rice and promoting the accumulation, distribution, and translocation of aboveground material by cultural measures are effective ways to improve the yield of direct-seeded rice.

The yield of rice can be decomposed into the spikelet per unit area (the number of panicles × spikelet per panicle), seed setting rate and 1000-grain weight, which are two components of reservoir capacity and filling. Ying et al. showed that a high reservoir capacity is an important characteristic of high-yielding rice, and stable, effective reservoir filling is the physiological basis of high-yielding rice [47]. In this study, paclobutrazol seed soaking increased the yield of direct-seeded rice and showed a trend of increasing and then decreasing with increasing paclobutrazol concentration (Figure 8). The regression analysis showed a decreasing trend when the concentration of paclobutrazol used for seed soaking was greater than 105 mg L^{-1} (Figure 9). In terms of yield components, paclobutrazol seed soaking mainly increased the yield by increasing the spikelet per unit area and the seed setting rate of direct-seeded rice (Figures 10 and 11). The spikelet per unit area in direct-seeded rice depends on the number of panicles and the spikelet per panicle. In the early stage of direct-seeded rice, using the appropriate concentration of paclobutrazol for seed soaking improved the seedling quality without affecting the seedling emergence; it also increased the number of stem tillers and the productive tillers and ensured a higher number of panicles per unit area in the later stage of fertility (Figures 1, 2 and 10; Table 1). Previous studies showed the correlation between the accumulation of dry matter at the heading stage and the number of surviving spikelets was significantly positive and that the correlation between the accumulation of dry matter at the heading stage and the number of degenerating spikelets was significantly negative [48,49]. In this study, the spikelet per panicle of direct-seeded rice was increased by paclobutrazol seed soaking, and there was a positive correlation between the spikelet per panicle and dry matter accumulation at the HD (Figures 10 and 12). The seed setting rate is closely related to grain filling in rice. Numerous studies have shown that the source of material for rice grain filling is the conversion of assimilates from nutrient organs to the spikelet before heading and the direct input of photosynthetic products to the spikelet after heading [50]. In the late stage of direct-seeded rice, paclobutrazol seed soaking ensured that it had better photosynthetic capabilities and material accumulation, which promoted grain filling in the late stage and increased the seed setting rate (Figures 3–8 and 10; Table 2). In addition, in this study, paclobutrazol seed soaking slightly reduced the thousand-grain weight of direct-seeded rice; it could be due to the fact that paclobutrazol seed soaking increased the spikelet per unit area and reduced the average dry matter increase distributed to individual seeds, resulting in a slight reduction in the thousand-grain weight (Figures 10 and 11).

5. Conclusions

In this study, using the appropriate concentration of paclobutrazol for seed soaking is an effective means of obtaining high yields of direct-seeded rice (Figure 13).

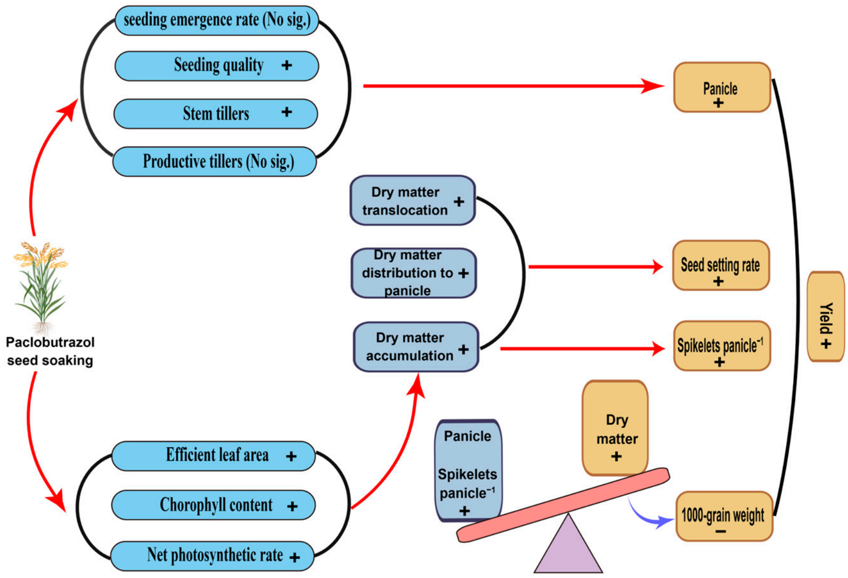

Figure 13. Diagram of paclobutrazol seed soaking to increase the yield of direct-seeded rice (the graphs were constructed with By Figdraw).

Author Contributions: Conceptualization, X.S., Y.G., W.L. and D.G.; methodology, X.S., Y.G., W.L. and D.G.; software, D.G. and J.L.; validation, J.L., J.D. and J.G.; formal analysis, D.G. and J.L.; investigation, J.L., J.D. and J.G.; data curation, W.L.; writing—original draft preparation, D.G. and W.L.; writing—review and editing, L.G. and Q.Z.; supervision, X.S. and Y.G.; project administration, X.S. and Y.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support this study will be shared upon reasonable request to the corresponding author.

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