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Exogenous Application of Lanthanum Chloride to Rice at Booting Stage Can Increase Chlorophyll Content, Modulate Chlorophyll Fluorescence and Promote Grain Yield Under Deficit Irrigation

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Abstract: To sustain agricultural productivity and safeguard global food security, and confront the escalating challenges posed by climate change and water scarcity, it is essential to enhance the growth and productivity of rice under water stress. This study investigated the effects of lanthanum chloride on the chlorophyll fluorescence characteristics and grain yield of rice under different irrigation modes. The rice cultivar H You 518 was selected and sprayed 20, 100, or 200 mg·L^{-1} lanthanum chloride at the booting and heading stages under deficit irrigation (where no rewatering was applied after the initiation of stress, allowing the water layer to evaporate naturally under high temperatures) or conventional irrigation (with daily rewatering to maintain a consistent water level). The results showed that the application of low concentrations lanthanum chloride promoted the chlorophyll content, whereas high concentrations decreased the chlorophyll content, under deficit irrigation, the effect of lanthanum chloride on the green fluorescence parameters of rice leaves at the booting stage was greater than that at the heading stage, and the booting stage was more sensitive to water deficit. The application of 100 mg·L^{-1} lanthanum chloride reduced the initial fluorescence (F0) and the non-photochemical quenching coefficient (qN); promoted the activity of leaf photosynthetic system II (PSII); and maximized the photochemical quantum yield (Fv/Fm), photochemical quenching coefficient (qP), and PSII relative electron transfer efficiency (ETR). Under deficit irrigation, this treatment significantly enhanced grain yield by increasing the thousand-grain weight, spikelet filling rate, and number of grains per panicle. These results suggest that spraying 100 mg·L^{-1} lanthanum chloride at the booting stage under deficit irrigation can effectively increase the chlorophyll content, thereby increasing the light energy conversion efficiency of the PS II reaction center, ultimately resulting in increased spikelet filling rate and grain yields.

Keywords: lanthanum effects; drought stress; leaf green fluorescence parameters; sustainability

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1. Introduction

Rice (*Oryza sativa* L.), a member of the Poaceae family, is the staple food for more than 65% of the population in China. As the world's largest rice producer, China is responsible

for approximately 30% of the total global rice production. The average yield of rice in China is 7113.4 kg per hectare, and the cumulative export volume of rice in 2023 was 1.6 million tons [1]. The production of rice largely relies on irrigation, and most rice farmers are accustomed to growing rice varieties with a traditional flooding method. However, China's per capita water resources are less than one-third of the world's average level [2], and the conservation of water resources has become an important prerequisite for sustainably ensuring social and economic development [3,4]. Irrigation is a necessary management measure that affects the growth and yield of rice [5], which has attracted widespread attention and has become a hotspot in agricultural research. Therefore, reasonable irrigation is the key to the sustainable development of rice production and food security. Studies have shown that controlling irrigation can greatly reduce water consumption and increase yield [6].

Lanthanum (La) is a rare element and is found in rare earth minerals, such as monazite and bastnaesite [7,8]. In soils, it can be transported and absorbed by rice and eventually enter the human food chain [9]. Scientific research has shown that lanthanum does not pose a direct risk of toxicity to human health [10,11]. Lanthanum has widely used in agricultural production in China, mainly in the cultivation of wheat [7], rice [12], soybean, maize [13], cabbage [14], rape [14,15], fiber crops [16], and other field crops [17,18]. Studies indicate that lanthanum influences a crop's physiology by enhancing its antioxidant defenses, increasing its heavy metal tolerance, and improving its nutrient dynamics, which are beneficial for cultivation [19]. However, higher concentrations adversely affect cellular processes like division, DNA integrity, nutrient uptake, and photosynthesis, resulting in plant toxicity [20].

Plant stress mostly results in a decrease in photosynthetic system II (PSII) electron transport and light energy conversion efficiency [21]. As chlorophyll fluorescence is closely related to each reaction process in photosynthesis, it can reflect the physiological processes of PSII [22]. Under environmental stress conditions, including water deficit, chlorophyll fluorescence parameters can change significantly, reflecting dynamic adjustments to photosynthesis [23]. This responsiveness makes chlorophyll fluorescence a valuable tool for assessing the impact of stress on plant growth and productivity [24]. Moreover, studies have shown that under water stress, changes in chlorophyll fluorescence can indicate alterations in the photosynthetic apparatus, which, in turn, affect plant growth and yield [23,25].

In photosynthesis research, chlorophyll fluorescence technologies have been widely used to investigate photosynthesis mechanisms [26], examine plant stress resistance [27], and predict crop yields [28]. In rice research, they have been applied in studies on water [29], temperature [30], nutrients [31], and salt stress [32]; however, the actions of rare earth elements in water-deficit conditions have not been investigated so far.

In this context, we used the rice cultivar H You 518 to study the effects of different concentrations of lanthanum chloride on the booting and heading stages of rice and to explore the effects on chlorophyll fluorescence characteristics and yield under two different irrigation regimes. The overall aim of this study is to enhance the quality and efficiency of rice production by applying optimal concentrations of lanthanum chloride to mitigate drought stress, offering a strategy for sustainable rice cultivation.

2. Materials and Methods

2.1. Plant Material

The rice cultivar H You 518 was used in this study. H You 518 is a hybrid cultivar introduced in 2010. The important reason for choosing H You 518 in this study was that this cultivar has been widely grown by rice farmers in the study region. The seeds were provided by the Rice Research Institute of Hunan Agricultural University, China.

2.2. Pot Experiment

A pot experiment was conducted under a rain shelter at Hunan Agricultural University, located in Changsha, Hunan province, China (28.22° N latitude, 112.93° E longitude). The site is characterized by a subtropical humid climate, with an average annual temperature of 16.8°C and an average relative humidity of 79%, and it receives about 1700 h of sunshine annually. The experimental soil was loess soil, with a pH of 6.5, containing 24.64 g/kg organic matter, along with alkaline hydrolyzed nitrogen, available phosphorus, and potassium at levels of 218.6, 19.6, and 152.3 $mg \cdot kg^{-1}$, respectively. Plastic pots (length: 54 cm, width: 40 cm, height: 25 cm) were filled with this soil to a depth of 20 cm. Pre-germinated seeds were sown in seedling trays, and uniformly sized seedlings were selected 25 days after sowing. Transplanting was performed with three hills per pot and two seedlings per hill. Before transplanting, each pot received 5.4 g of compound fertilizer ($N + P_2O_5 + K_2O \geq 35\%$, 15-8-12) and 1.33 g of urea—fertilization rates that are in line with local agricultural practices in the experimental area. Insect and disease management was carried out following conventional pot testing methods, and weeds were controlled through manual removal.

The seedlings were irrigated at the booting and heading stages, with two irrigation management treatments imposed: deficit irrigation (A) and conventional irrigation (B). In (A), after 9 days without irrigation, the soil layer was rehydrated with a 2–3-cm water depth, while in (B), a floodwater depth of about 2–3 cm was maintained from transplanting until maturity. Additionally, within each irrigation treatment, lanthanum (Sinopharm Chemical Reagent Co. Ltd., Shanghai, China) chloride was applied to the foliage at three concentrations: 20 $mg \cdot L^{-1}$ (A1, B1), 100 $mg \cdot L^{-1}$ (A2, B2), and 200 $mg \cdot L^{-1}$ (A3, B3). Control groups (CKA, CKB) were sprayed with water. For spraying, we added 0.1% of Tween 20, and spraying was performed from 4:00 to −6:00 pm over 3 days. On the 3rd, 5th, 7th, and 9th days after the first spraying, samples were taken for index determination.

2.3. Sampling and Measurements

In our study, each treatment was replicated three times. At the booting stage, we selected the second leaf, and at the heading stage, the flag leaf was chosen for analysis to ensure a comprehensive assessment of the treatment effects across different developmental stages. Immediately post-harvest, leaves were gently cleaned, placed in moisture-proof plastic bags, and quickly transferred to insulated containers with ice packs to maintain low temperatures during transport. Upon arrival at the laboratory, leaves were snap-frozen in liquid nitrogen to preserve chlorophyll and other biochemical components and then stored at −80°C until further analysis. The ethanol extraction method, modified from the Aron method [33], was employed to measure the chlorophyll levels, providing a reliable assessment of pigment concentrations.

Chlorophyll fluorescence parameters were assessed during the critical stages of booting and heading. Specifically, we targeted the middle section of the penultimate leaf on the main stem of rice plants. Each treatment was measured in triplicate to ensure data reliability. Using a portable chlorophyll fluorescence fluorometer (Czech FluorPen FP 100-MAX, Photon Systems Instruments, Brno, Czech Republic), we obtained the chlorophyll fluorescence kinetics curve. Prior to measurement, leaves were dark-adapted for 20 min to ensure basal fluorescence levels. The saturation pulse was set to approximately 3000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with actinic light at 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. From these measurements, we derived parameters including the initial fluorescence (F0), maximum photochemical quantum yield (Fv/Fm), photochemical quenching coefficient (qP), and non-photochemical quenching coefficient (qN).

Offering insights into the efficiency of photosynthetic electron transport, the electron transport rate (ETR) was calculated using the formula [34]:

$$ETR = PAR \times (\Delta F/Fm') \times 0.84 \times 0.5 \quad (1)$$

At the maturity stage, we determined the plant height, number of panicles per plant, seed setting rate, total grain number, ear length, and 1000-grain weight. The yield of each pot was calculated, with each treatment repeated three times to ensure the robustness of our yield assessments.

2.4. Statistical Analysis

Data were subjected to an analysis of variance (ANOVA) using SPSS 19.0 for Windows. In cases of statistical significance ($p \leq 0.05$), the mean values were further compared using the LSD (Least Significant Difference). The graphs were plotted using GraphPad Prism 8.0.

3. Results

3.1. Leaf Chlorophyll Content

Spraying with 20 mg·L^{-1} and 100 mg·L^{-1} lanthanum chloride increased the chlorophyll a content under both irrigation methods, while the 200 mg·L^{-1} treatment reduced the chlorophyll a content to a certain extent (Figure 1). In particular, the chlorophyll a content was the highest on the 5th day after 20 mg·L^{-1} treatment under deficit irrigation and the 100 mg·L^{-1} treatment under conventional irrigation the booting stage; the values were 36.0% and 24.5% higher than those for CKA (control for deficit irrigation) and CKB (control for conventional irrigation), respectively. Under the deficit irrigation conditions, the chlorophyll a content was the lowest on the 9th day after the 200 mg·L^{-1} treatment, with a level that was 23.5% lower than that for CKA, while under the conventional irrigation conditions, the chlorophyll a content was the lowest on the 7th day after the 200 mg·L^{-1} treatment, with a level that was 11.7% lower than that for CKB. The chlorophyll a content was the highest on the 9th and 3rd days after the 20 mg·L^{-1} treatment under the two irrigation methods at the heading stage, with levels that were 17.1% and 22.1% higher than those for CKA and CKB, respectively. (Figure 1). These results show that lanthanum chloride can promote the accumulation of chlorophyll b in leaves, and the overall effect is better at the heading stage than the booting stage. (Figure 1). After spraying with lanthanum chloride, in each treatment, carotenoids were first promoted and then inhibited (Figure 1). The effect of spraying lanthanum chloride on the total chlorophyll in each treatment was roughly the same as that on chlorophyll a, which may be due to the high proportion of chlorophyll a with regard to the total chlorophyll.

3.2. Initial Fluorescence F0 on Rice Leaves

The initial fluorescence, F0, represents the fluorescence when the PSII reaction center is fully open, and any increase is due to the reversible or irreversible inactivation of the PSII reaction center [14]. When rice is under water deficit, the F0 value depends on the duration of the stress and the variety of the rice (Figure 2). In the booting stage, the F0 value for the deficit irrigation control group, CKA, was higher than that for the conventional irrigation control group, CKB; in the heading stage, that for CKA was higher than that for CKB only after 9 days. Spraying lanthanum chloride at the booting stage generally reduced the F0 value under deficit irrigation. In particular, the 100 mg·L^{-1} treatment of lanthanum chloride exhibited the lowest F0 value at 7 days post-treatment, with a level that was 12.5% lower than that for CKA. The range of changes between treatments at the heading stage was smaller than that at the booting stage. After the 200 mg·L^{-1} treatment,

the F0 value was always reduced, and it was 7.2% lower than that for CKA on the 5th day after treatment.

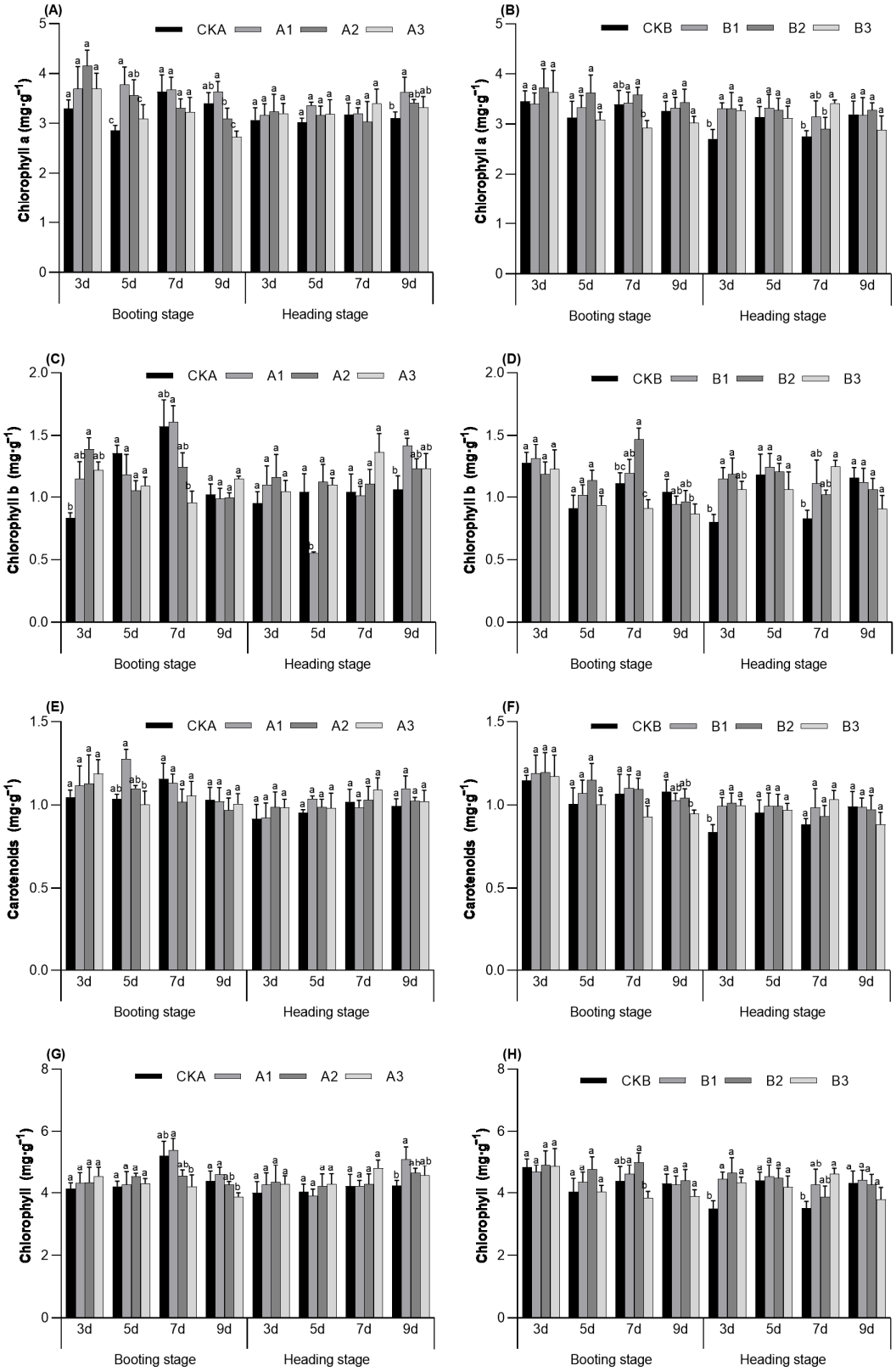


Figure 1. Effect of lanthanum chloride on chlorophyll content of rice leaves under different irrigation modes. (**A**,**C**,**E**,**G**): deficient irrigation. (**B**,**D**,**F**,**H**): conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SEs (n = 3). Means with the same letters are not significantly different according to LSD (0.05).

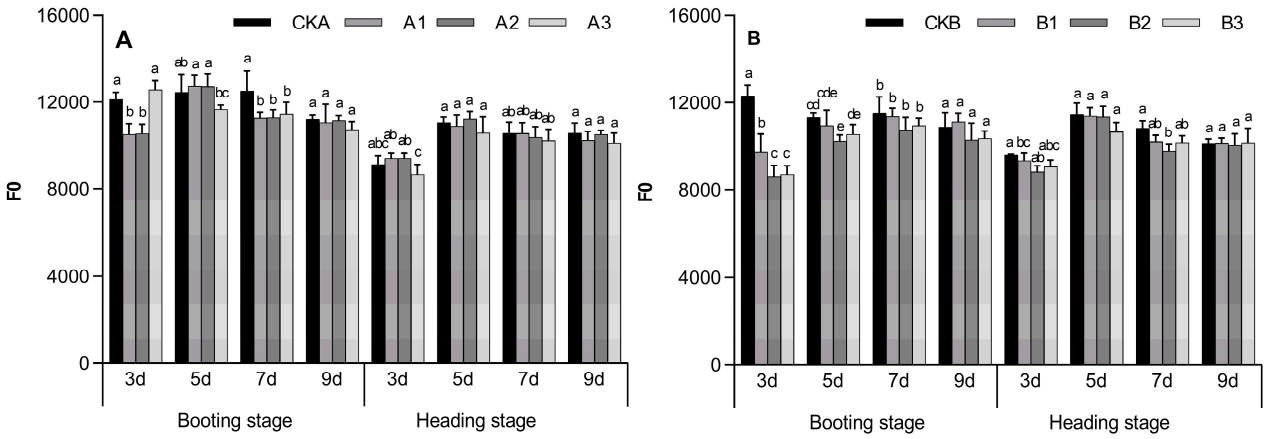


Figure 2. F0 changes after spraying lanthanum chloride under different irrigation modes. (**A**) Deficient irrigation. (**B**) Conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SE (n = 3), Means with the same letters are not significantly different according to LSD (0.05).

3.3. Maximum Photochemical Quantum Yield (Fv/Fm) on PSII

The ratio Fv/Fm represents the maximum photochemical quantum yield, which is used to measure the initial light energy conversion efficiency and the PSII potential activity of plant leaves [14,31]. Fv/Fm is not affected by the species or growth setting under normal conditions, but it does show a significant decline under stress conditions. The results showed that the Fv/Fm value decreased under the water-deficient modes (Figure 3). At the booting stage, under the two irrigation methods, the Fv/Fm values at 5 and 9 days after treatment with 20 mg·L^{-1} and the Fv/Fm value at 7 days after treatment with 100 mg·L^{-1} were higher than that for CKA. On the 3rd and 5th days after treatment with lanthanum chloride, the Fv/Fm value decreased as the concentration of lanthanum chloride increased. At the heading stage, under conventional irrigation conditions, the Fv/Fm value was significantly increased 5 days after lanthanum chloride treatment compared with the control. In addition, the 3rd Fv/Fm value after spraying lanthanum chloride at the heading stage was first at a high value, then dropped sharply, and then increased with the passage of time (Figure 3).

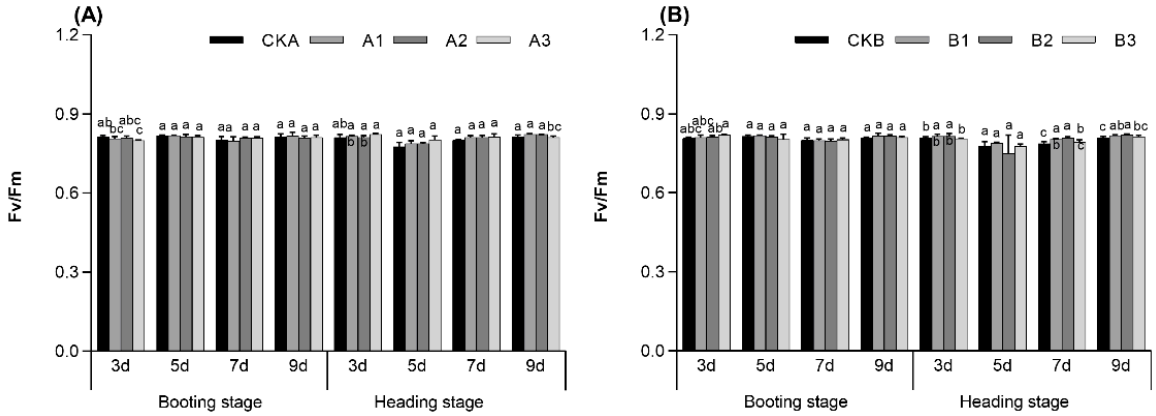


Figure 3. Fv/Fm changes after spraying lanthanum chloride under different irrigation modes. (**A**) Deficient irrigation. (**B**) Conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SE (n = 3), Means with the same letters are not significantly different according to LSD (0.05).

3.4. Photochemical Quenching Coefficient (qP)

The qP value reflects the openness of the PSII reaction center [14]. As shown in Figure 4, in the water-deficient irrigation regime at the booting stage, the qP value increased at 3 and 9d after treatment with 100 mg·L^{-1} to values 5.7% and 5.1% higher than that for the CKA, respectively. After the application of 200 mg·L^{-1}, the qP value increased continuously. The qP value for each treatment in the heading stage was lower than that for the control, and in the conventional irrigation regime, the qP value decreased less compared with CKB at higher lanthanum chloride concentrations.

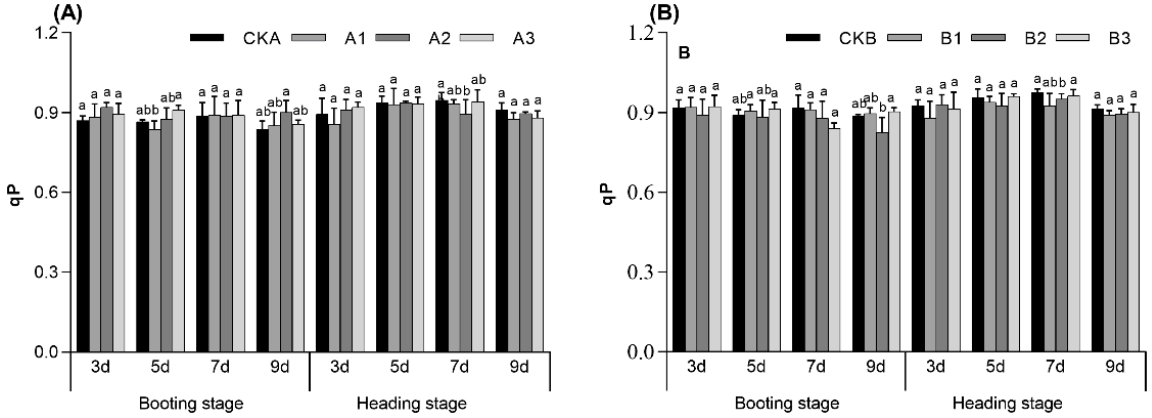


Figure 4. qP changes after spraying lanthanum chloride under different irrigation modes. (**A**) Deficient irrigation. (**B**) Conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SE (n = 3), Means with the same letters are not significantly different according to LSD (0.05).

3.5. Non-Photochemical Quenching Coefficient (qN)

The qN value reflects a change in the ability of plants to dissipate heat. The energy absorbed by natural pigments is released in the form of heat dissipation, which is then used in photosynthetic electron transfer, to increase photosynthetic efficiency [14]. The qN value at the booting stage shows an overall downward trend over time, while at the heading stage, the qN value shows an upward trend over time (Figure 5).

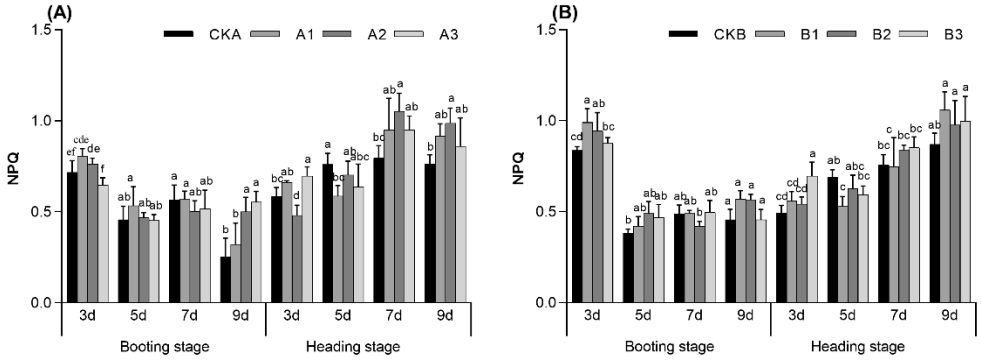


Figure 5. qN changes after spraying lanthanum chloride under different irrigation modes. (**A**) Deficient irrigation. (**B**) Conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SE (n = 3), Means with the same letters are not significantly different according to LSD (0.05).

Under the water-deficient irrigation regime at the booting stage, the qN values were reduced to different degrees at 7 and 3d after treatment with 20 and 100 mg·L^{-1}. After 9 days, the qN values for each treatment were higher than that for CKA, with significant

differences between the 100 and 200 mg·L^{-1} treatments. At the heading stage, spraying with lanthanum chloride effectively increased the qN values on the 7th and 9th days after treatment; in particular, the treatment with 100 mg·L^{-1} showed values that were 28.0% and 19.6% higher than that for CKA. Similar results were obtained under the conventional irrigation treatment. The qN values were lower than that for CKB on the 3rd and 5th days but were improved in the treatment groups with 100 and 200 mg·L^{-1} on the 7th and 9th days.

3.6. Maximum Relative Electron Transport Efficiency (ETR) in PSII

The ETR represents the apparent electron transfer efficiency under the actual light intensity [34]. The ETR value increased shortly after spraying with lanthanum chloride under the different irrigation regimes at the booting stage, with higher concentrations having a greater effect (Figure 6). The ETR value increased significantly by 11.8% on the 3rd day after treatment with 200 mg·L^{-1} under water-deficient irrigation, while under conventional irrigation, it increased by 4.5% on the 3rd day after treatment with 100 mg·L^{-1}. After the heading-stage treatment, the ETR value only slightly increased. The treatment with 200 mg·L^{-1} had a significant effect on the ETR value under the water-deficient irrigation regime; the value was 7.5% higher than in CKA. The ETR was 3.0% higher than that for CKB after the treatment with 20 mg·L^{-1} under the conventional irrigation mode.

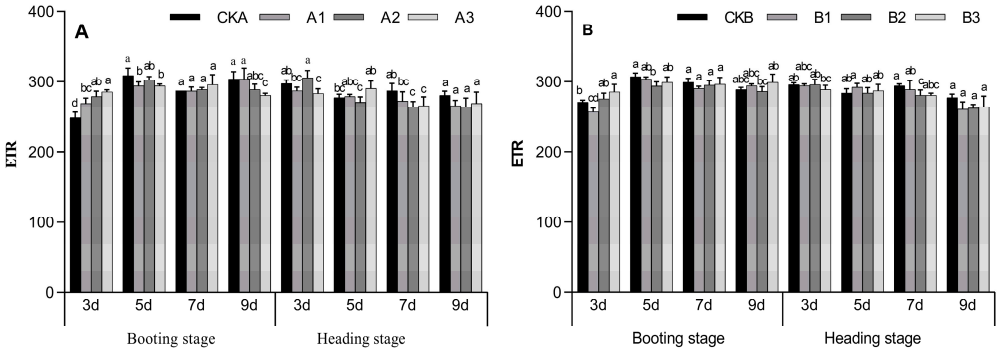


Figure 6. ETR changes after spraying lanthanum chloride under different irrigation modes. (**A**) Deficient irrigation. (**B**) Conventional irrigation. CK, 1, 2, and 3 represent four concentrations of 0 mg·L^{-1}, 20 mg·L^{-1}, 100 mg·L^{-1}, and 200 mg·L^{-1}, respectively. Vertical bars represent SE (n = 3), Means with the same letters are not significantly different according to LSD (0.05).

3.7. Grain Yield and Yield Attributes

At the booting stage, the application of lanthanum chloride significantly increased the plant height, grain weight, and yield, irrespective of the irrigation regime (Table 1). The treatment with 100 mg·L^{-1} in the water-deficient irrigation group significantly increased the grain weight, spikelet filling rate, and number of spikelets per panicle, and it ultimately increased the theoretical yield by 16.0% compared with CKA. In the conventional irrigation treatment, the application of 20 and 100 mg·L^{-1} significantly increased the grain weight compared with CKB, finally increasing the theoretical yield. However, the panicle number per hill after the application of 200 mg·L^{-1} was lower than that in CKB, with a lower theoretical yield. The actual yields for the two irrigation methods were in the order 100 mg/L > 20 mg·L^{-1} > CK > 200 mg·L^{-1}, and the yield for the 100 mg·L^{-1} treatment under conventional irrigation was significantly increased by 24.3% compared with that for CKB (Table 1).

Table 1. Effect of lanthanum chloride on seed yield and yield components of rice under different irrigation modes.

Stage	Treatments	Plant Height (cm)	Panicles Hill^{-1}	Spikelet Filling Rate	Spikelets per Panicle	Grain Weight (mg)	Theoretical Yield (kg 667 m^{-2})	Actual Output (g pot^{-1})
Booting stage	CKA	84.95 ± 1.05 b	12.67 ± 1.76 a	0.77 ± 0.07 a	92.91 ± 14.99 a	23.64 ± 0.25 c	412.05 ± 49.85 ab	76.1 ± 4.7 a
	A1	91.39 ± 0.95 a	12.67 ± 0.33 a	0.56 ± 0.12 a	85.3 ± 1.35 a	24.23 ± 0.47 bc	293.23 ± 66.96 b	86.94 ± 3.25 a
	A2	88.61 ± 1.34 a	12.33 ± 1.2 a	0.8 ± 0.01 a	100.86 ± 4.51 a	24.29 ± 0.5 bc	477.82 ± 30.5 a	91.99 ± 6.35 a
	A3	85.06 ± 0.77 b	11.33 ± 0.33 a	0.8 ± 0.06 a	91.79 ± 4.94 a	23.95 ± 0.3 bc	397.42 ± 31.14 ab	78.97 ± 3.34 a
	CKB	82.05 ± 1.13 b	11 ± 0.58 a	0.79 ± 0.08 a	96.47 ± 7.89 a	24.31 ± 0.12 bc	402.16 ± 27.5 a	86.96 ± 8.96 ab
	B1	89.14 ± 1.15 a	12 ± 1 a	0.84 ± 0.02 a	87.49 ± 11.94 a	25.45 ± 0.26 a	436.48 ± 25.93 a	99.59 ± 4.33 ab
	B2	85.22 ± 1.83 ab	10.33 ± 0.88 ab	0.78 ± 0.01 a	98.46 ± 4.33 a	25.83 ± 0.36 a	417.95 ± 67.47 a	108.07 ± 9.02 a
	B3	86.47 ± 1.23 a	8.33 ± 0.33 b	0.84 ± 0.02 a	111.08 ± 2.5 a	25.03 ± 0.36 ab	392.04 ± 25.41 a	80.34 ± 6.51 b
Heading stage	CKA	79.38 ± 1.68 a	9.67 ± 0.88 a	0.84 ± 0.01 a	100.54 ± 4.46 a	24.03 ± 0.83 c	397.71 ± 65.29 a	82.99 ± 4.95 a
	A1	80.34 ± 1.44 a	11.67 ± 1.33 a	0.8 ± 0.04 a	100.26 ± 7.35 a	24.18 ± 0.54 bc	444.35 ± 22.48 a	72.26 ± 2.59 a
	A2	78.34 ± 1.08 a	13 ± 2.65 a	0.78 ± 0.03 a	103.9 ± 8.93 a	23.79 ± 0.7 c	474.51 ± 41.71 a	72.79 ± 6.71 a
	A3	83.28 ± 2.14 a	12.67 ± 1.33 a	0.82 ± 0.06 a	109.15 ± 6.54 a	24.56 ± 0.37 abc	552.09 ± 53.41 a	79.32 ± 8.44 a
	CKB	87.73 ± 1.6 a	11.67 ± 1.2 a	0.86 ± 0.01 a	105.04 ± 7.75 a	25.59 ± 0.28 ab	533.54 ± 12.83 a	87.6 ± 5.49 a
	B1	84.82 ± 1.65 a	10 ± 1 a	0.85 ± 0.01 ab	93.76 ± 4.44 a	25.19 ± 0.5 a	399.36 ± 39.01 ab	81.73 ± 5.37 a
	B2	84.71 ± 1.35 a	9.67 ± 1.2 a	0.86 ± 0.01 ab	92.63 ± 1.61 a	25.65 ± 0.27 a	390.29 ± 35.69 b	82.09 ± 8.36 a
	B3	85.42 ± 2.06 a	9.33 ± 0.33 a	0.82 ± 0.01 b	91.88 ± 6.86 a	24.73 ± 0.96 a	354.74 ± 54.11 b	72 ± 6.09 a

Note: Different small letters in the same column indicate a significant difference at the 0.05 level.

The application of lanthanum chloride at the heading stage in the conventional irrigation treatment resulted in a lower plant height, while the application of 20 and 200 mg·L^{-1} in the water-deficient irrigation group increased the plant height. Under water-deficient irrigation, the application of 20 and 200 mg·L^{-1} increased the panicle number per hill, number of spikelets per panicle, and grain weight, while the spikelet filling rate was reduced. However, the final theoretical yield was higher than that for CKA. The panicle number, spikelet filling rate, and grain weight for each treatment under conventional irrigation were lower than those for CKB, resulting in lower final theoretical and actual yields (Table 1).

3.8. Two-Way ANOVA Analysis of Lanthanum Chloride and Irrigation Interactions

The analysis revealed no significant interactive effects between these two factors on the measured variables (Table 2).

Table 2. Interaction effects Lanthanum Chloride Concentration and Irrigation Methods.

Index \ Period	Booting Stage	Heading Stage
Chlorophyll a	$F_{IM\times c}$ = 1.61 ns	$F_{IM\times c}$ = 0.25 ns
Chlorophyll b	$F_{IM\times c}$ = 0.64 ns	$F_{IM\times c}$ = 2.05 ns
Carotenoids	$F_{IM\times c}$ = 1.70 ns	$F_{IM\times c}$ = 0.27 ns
Chlorophyll	$F_{IM\times c}$ = 1.76 ns	$F_{IM\times c}$ = 0.64 ns
F0	$F_{IM\times c}$ = 2.08 ns	$F_{IM\times c}$ = 0.57 ns
Fv/Fm	$F_{IM\times c}$ = 0.38 ns	$F_{IM\times c}$ = 0.48 ns
qP	$F_{IM\times c}$ = 3.71 ns	$F_{IM\times c}$ = 0.09 ns
NPQ	$F_{IM\times c}$ = 0.02 ns	$F_{IM\times c}$ = 0.13 ns
ETR	$F_{IM\times c}$ = 0.45 ns	$F_{IM\times c}$ = 0.20 ns

Note: IM represents the irrigation method, C represents the concentration, and ns indicates no significant interaction effect.

4. Discussion

Changes in the chlorophyll content affect the capture and transmission of the original light energy, thereby affecting chlorophyll fluorescence [34]. Previous studies have shown that chlorophyll b has the function of absorbing and transmitting light energy during photosynthesis [35]. In this study (Figure 1), drought stress significantly reduced the chlorophyll content in rice plants; however, the application of exogenous $LaCl_3$ effectively alleviated this decrease and even increased the chlorophyll content to some extent. The application of 100 mg·L^{-1} $LaCl_3$ at the booting stage had the most significant positive impact on chlorophyll a, chlorophyll b, carotenoids, and the total chlorophyll content, indicating that an appropriate amount of $LaCl_3$ can enhance the photosynthetic capacity

of rice at critical growth stages. In contrast, the application of 20 mg·L^{-1} $LaCl_3$ at the heading stage had the greatest effect on the chlorophyll content, which may be related to the sensitivity of rice to water stress at this stage. This suggests that the application of $LaCl_3$ can effectively mitigate the closure of leaf stomata under drought stress, promote the absorption of CO_2 by plants, and thus enhance their photosynthetic capacity. During conventional irrigation, spraying with $LaCl_3$ also increased the chlorophyll content to some extent, demonstrating the promotive effect of $LaCl_3$ on rice growth under different irrigation conditions. Wang et al. confirmed that low concentrations of La3+ can activate ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), thereby increasing the photosynthetic rate of plants [36]. The chlorophyll fluorescence parameters of rice leaves can reflect the operation of PSII and, subsequently, the plant's photosynthetic efficiency [21]. A decrease in the total chlorophyll content is a typical sign of pigment photo-oxidation and chlorophyll degradation, and the regulation of chlorophyll metabolic biosynthesis in plants depends on the intensity and type of environmental stress. Spraying with lanthanum chloride ($LaCl_3$) can effectively alleviate the reduction in the chlorophyll content in rice plants caused by drought stress, possibly because lanthanum controls the degradation of plant photosynthetic pigments, protecting the photosynthetic reaction system and thereby enhancing the photosynthetic capacity of rice plants under drought stress. This study showed that spraying with lanthanum chloride effectively reduced the F0 value, a trend which is in line with the chlorophyll content (Figure 2) and consistent with the findings of Li [37]. During water-deficient irrigation, the concentrations of 100 and 20 mg·L^{-1} were optimal for the booting and heading stages, respectively. The chlorophyll content during the heading stage remained high after the treatment with 200 mg·L^{-1}, which may explain the consistently lower F0 values. The change in F0 during the booting stage exceeded that during the heading stage, indicating that water stress may lead to a decrease in photosynthetic efficiency, thus affecting the F0 value (Figure 2). This suggests that plants have a higher water requirement at this stage, which is consistent with the research results of Wang et al. [38]. The Fv/Fm ratio represents the maximum photochemical quantum yield and reflects the photochemical efficiency of PSII [31,39]. The Fv/Fm value of plant leaves under normal growth conditions is generally stable at around 0.8 [40]. When subjected to water stress, Fv/Fm and qP values decrease significantly, while qN increases [41]. Generally, Fv/Fm can be used to rapidly monitor plant stress [31]. In previous studies, drought stress was found to reduce the maximum photochemical efficiency (Fv/Fm), the actual photochemical efficiency (ΦPSII), the photochemical quenching coefficient (qP), and the PSII electron transport efficiency (ETR), while increasing the non-optical quenching coefficient (qN) of maize plants [42]. In this study, the application of 100 mg·L^{-1} at the booting stage increased the Fv/Fm and qP values and decreased the qN value (Figures 3 and 4), indicating that lanthanum chloride facilitates the activity of the PSII reaction center. The qN value showed an overall downward trend at the booting stage, while in the heading stage, it showed an overall upward trend. This indicates that the PSII reaction center at the booting stage has a high electron transfer activity, and the plant's ability to dissipate heat is gradually reduced; however, the activity at the heading stage is reduced. Lanthanum chloride can increase the ETR value, and the application of 200 mg·L^{-1} lanthanum chloride is more effective than a treatment using only 100 mg·L^{-1} (Figure 6).

Different irrigation methods at the booting and heading stages of rice have a great impact on yield components and the final yield (Table 1). Previous studies found that under water shortage, during the booting stage, rice plants have a lower height, associated with a lower number of panicles pre hill [43]. Huang et al. [44] and Li et al. [45] stated that reductions in more than two indicators among the number of panicles per hill, spike number, grain weight, and spikelet filling rate may lead to a lower yield. Yang et al. [46] also

found that water shortages at the heading stage mainly caused yield reductions by affecting the spikelet filling rate and the grain weight. In this study, the height of plants treated with lanthanum chloride under water-deficient irrigation significantly improved, and the number of panicles pre hill reached normal levels, with high values for the grain weight, kernel number, and spikelet filling rate after the treatment with 100 $mg \cdot L^{-1}$ lanthanum chloride (Table 1). The late compensatory effect was obvious, and the theoretical and actual yield were the highest, which is consistent with the results of Guo et al. [47]. In the heading stage, lanthanum chloride mainly increased the number of panicles per hill, thereby increasing the theoretical yield. This is likely related to the effects of $LaCl_3$ treatment on enhancing the photosynthetic efficiency and water use efficiency of rice, as well as increasing the activity of antioxidant enzymes in the plants. However, due to a lower spikelet filling rate, the actual yield was lower. Generally, rice plants are more sensitive to lanthanum chloride in the booting stage than in the heading stage (Table 1).

5. Conclusions

A moderate amount of the rare-earth element lanthanum can enhance stress resistance, improve photosynthetic capacity, and promote nutrient absorption and utilization in plants, thereby increasing crop yields. Our study showed that spraying lanthanum chloride solution onto rice significantly improved the chlorophyll fluorescence parameters and rice yield under various irrigation regimes, with a pronounced effect at the booting stage. An amount of 100 $mg \cdot L^{-1}$ lanthanum chloride can improve the absorption and use of light energy by the PSII light system at the booting stage under conventional irrigation, thereby enhancing the photosynthetic capacity of plants, promoting their growth and development and laying a foundation for high grain yields. Looking ahead, we will focus on two main objectives: exploring $LaCl_3$-mediated drought tolerance in rice at the transcriptional and metabolic levels through mutant construction and gene analysis, and developing $LaCl_3$-based fertilizers and foliar fertilizers to apply our findings in agricultural practice.

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