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Effects of Zeolite on Physiological Characteristics and Grain Quality in Rice under Alternate Wetting and Drying Irrigation

Yidi Sun *, Jigan Xie, Huijing Hou, Min Li, Yitong Wang and Xuetao Wang

College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China; hjhou@yzu.edu.cn (H.H.)
* Correspondence: yidisun0626@outlook.com; Tel.: +86-15698824626

Abstract: Background: Zeolite (Z) is gradually used in rice production due to its holding ability for water and nutrients, but limited information is available on how its physiological function affects rice grain yield and quality under water stress. Methods: This study aimed to investigate the effect of Z application on rice physiological characteristics, dry matter and nitrogen accumulation, grain yield and quality under continuous flooding (CF) and alternate wetting and drying irrigation (AWD). Results: The results showed that, compared with CF, AWD reduced leaf SPAD, root bleeding intensity, aboveground dry matter and nitrogen accumulation, resulted in lower grain yield without Z application, but improved root–shoot ratio and root N accumulation. Z application increased dry matter and N accumulation, and subsequent grain yield by improving leaf SPAD and root bleeding intensity. Both AWD and Z application improved water use efficiency. AWD reduced head rice rate, chalky rice rate and chalkiness, but improved the taste value by increasing the breakdown and reducing the setback. Z application improved protein content, reduced breakdown and setback, but increased chalky rice rate and chalkiness. Conclusions: These results indicated that AWD and Z application could achieve several benefits including improved grain yield, grain quality and water use efficiency.

Keywords: zeolite; alternate wetting and drying irrigation; rice; physiological characteristics; grain quality

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1. Introduction

Rice has an important strategic position in global food production. China is a major rice producer and rice consumer; it is necessary to improve the rice grain yield to meet the future demand for rice as the planting area is decreasing year by year [1]. Rice is a water-intensive crop and its traditional flooded irrigation regime leads to high water consumption and low water use efficiency, which is contrary to the increasingly short supply of water resources in China [2]. Therefore, it is necessary to develop a water-saving irrigation regime in paddy fields in order to ensure water security and food security with minimum water consumption in China.

Alternate wetting and drying irrigation is the most widely used as an effective water-saving irrigation regime, which reduces the water consumption by 15~30%, relative to traditional flooding irrigation [3], but its effect on the physiological characteristics and grain yield are still controversial [4–6]. Some studies suggested the soil was in a state of water saturation under flooding irrigation, which might reduce the oxidative activity of rice roots, and then inhibit root growth and development, thus it was difficult to ensure high grain yield and excellent rice grain quality [5,6]. Paddy soil moisture was in an alternating saturated and unsaturated environment, and the soil aeration was improved under AWD. The improved soil aeration was beneficial in maintaining strong root activity, and then the ability of roots to absorb nutrients was enhanced, which improved the rice physiological function and grain yield under AWD [7,8]. Additionally, both NH_4^+-N and NO_3^--N were present in soil under AWD due to the enhanced nitrification reaction caused by the increase in dissolved oxygen in the paddy field, which enhanced root growth and improved nitrogen accumulation and yield of rice [9]. However, some studies indicated AWD caused nitrogen loss in the form of N_2 or N_2O due to the enhanced soil nitrification–denitrification process, which reduced nitrogen accumulation in plants and thus reduced rice grain yield. There are also some reports that showed AWD had no significant effect on rice grain yield. Rice quality is the second most important factor in determining the economic benefits of rice after yield [10]. The rice grain quality was not only affected by its own genetic characteristics, but also related to external environmental conditions such as cultivation patterns. The previous study found moderate AWD significantly improved head rice rate while it decreased chalkiness, and thus the rice quality was better [11]. Other studies found that moderate alternate wetting and drying irrigation at the grain filling stage improved appearance quality, increased breakdown and decreased setback of rice, but severe alternate wetting and drying irrigation showed the opposite effects [12]. Although most studies have shown that alternate wetting and moderate drying irrigation was beneficial to the improvement in rice grain quality, previous research results showed that it reduced the appearance and nutritional quality of rice [13]. At present, the effects of AWD irrigation on quality are contradictory [14,15]. Thus, it is necessary to clarify the impact of AWD irrigation on rice quality, and solve the possible negative effects on rice grain yield.

Zeolite, as a soil conditioner, is a type of aqueous porous aluminosilicate crystal mineral, with a lattice-like structure composed of (Si, Al, O) tetrahedra; thus, it has an intensive affinity for water and fertilizer due to its strong ion exchange capacity, high adsorption and hydration–dehydration properties, so it had significant advantages in improving crop yield [16]. Therefore, zeolite is widely used in the agricultural and environmental fields [16–21]. Many scholars pointed out that zeolite had remarkable results on improving the growth and physiological traits of crops and yields such as soybean [17], corn [18] and wheat [19] under different soil conditions. In addition, zeolite could continuously provide water molecules during drought stress periods, and promoted the diffusion of water molecules to the root zone during the irrigation period, so as to alleviate the negative effects of drought stress on crop growth. Some field experiments showed that zeolite had a more significant yield increase effect under drought stress conditions [20–23]. We anticipate that the high ion exchange and adsorption properties of zeolite for ammonium ion would have an impact on soil nitrogen supply in paddy fields, which, in turn, might affect rice grain quality. However, there were few studies on the effect of zeolite on rice grain quality. Whether an integrated AWD and zeolite management pattern could make full use of the incentivizing effect of water and fertilizer in improving rice yield, water use efficiency and grain quality needed to be further verified. Therefore, the objectives of this study were to further investigate the effects of Z on the physiological characteristics, grain yield and quality of rice in the AWD paddy field through a field experiment.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out at the Donggang Irrigation Experiment Station in Dandong, Liaoning Province (113°34′43″ E, 39°52′38″ N). Donggang has a continental monsoon climate in the north temperate humid region, with an annual average temperature of 8.4 °C, an annual precipitation of 900–1000 mm and a sunlight duration of 2484.3 h. The soil texture is silt loam, and the initial physical and chemical properties of soil were shown in Table 1 [24]. The daily average temperature and reference crop evapotranspiration during the rice growing period were shown in Figure 1. Meteorological data were observed by an automatic weather station located on the west side of the experimental station. ET_0 is estimated by the Penman–Monteith method recommended by the Food and Agriculture Organization of the United Nations.

Table 1. Physicochemical properties of the soil before the field experiment and of the clinoptilolite zeolite.

Soil Properties		Chemical Composition of Zeolite (%)			
Bulk density	1.39 g m^{-3}	SiO_2	67.09	FeO	0.07
pH	6.76	Al_2O_3	12.44	MnO	0.03
Total N,	2833 kg ha^{-1}	CaO	6.51	P_2O_5	0.03
$NH_4{}^+$-N,	8.0 kg ha^{-1}	MgO	1.22	Loss on ignition	10.1%
$NO_3{}^-$-N	9.2 kg ha^{-1}	K_2O	1.2	CEC	142 $cmol_c$ kg^{-1}
Available P	53 mg kg^{-1}	Fe_2O_3	0.78	SSA	670 m^2 g^{-1}.
Exchangeable K	165 mg kg^{-1}	Na_2O	0.26		
CEC	15 $cmol_c$ kg^{-1}	TiO_2	0.09		

Notes: CEC, cation exchange capacity; SSA, specific surface area.

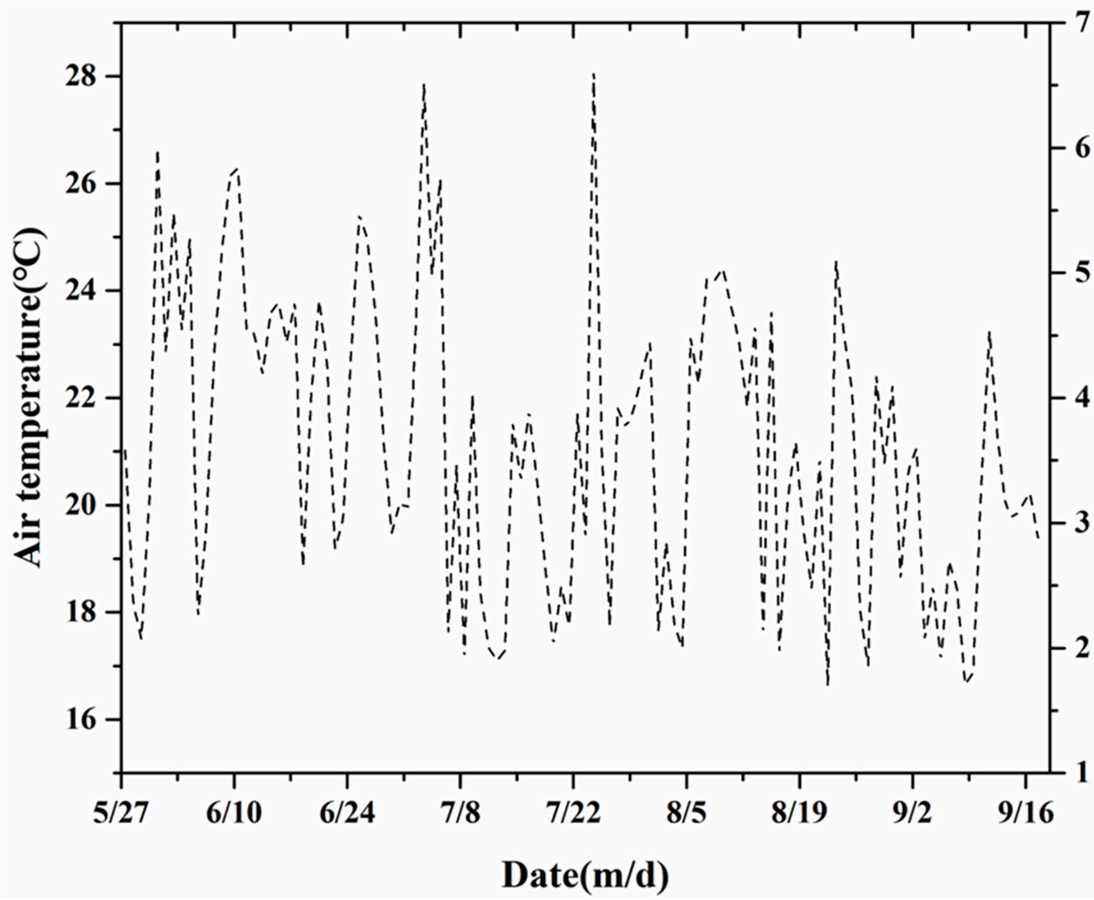

Figure 1. Daily average air temperature during rice-growing period. Air temperature was measured at a weather station close to the experimental site.

2.2. Experimental Design and Management

The experiment was adopted in a split-plot design with two factors of irrigation regime(I) and zeolite application rate (Z), with three replicates (lysimeters) in 2017 and 18 treatments in total, $I_{CF}Z_0$, $I_{CF}Z_5$, $I_{CF}Z_{10}$, $I_{AWD}Z_0$, $I_{AWD}Z_5$, $I_{AWD}Z_{10}$, respectively. The main-plots were irrigation regimes with continuous flooding irrigation (CF) and alternate wetting and drying irrigation (AWD); the sub-plots were rates of Z addition with 0 t·ha^{-1} (Z_0), 5 t·ha^{-1} (Z_5) and 10 t·ha^{-1} (Z_{10}). The experiment was carried out in a non-weighing lysimeter with automatic canopy, and the specifications of each lysimeter were 2.55 m (length) × 2.62 m (width) × 2.55 m (height) = 6.67 m^2. The lysimeter was cast from reinforced concrete to prevent lateral cross flow of moisture and nutrients. The experimental design and layout are shown in Figure 2.

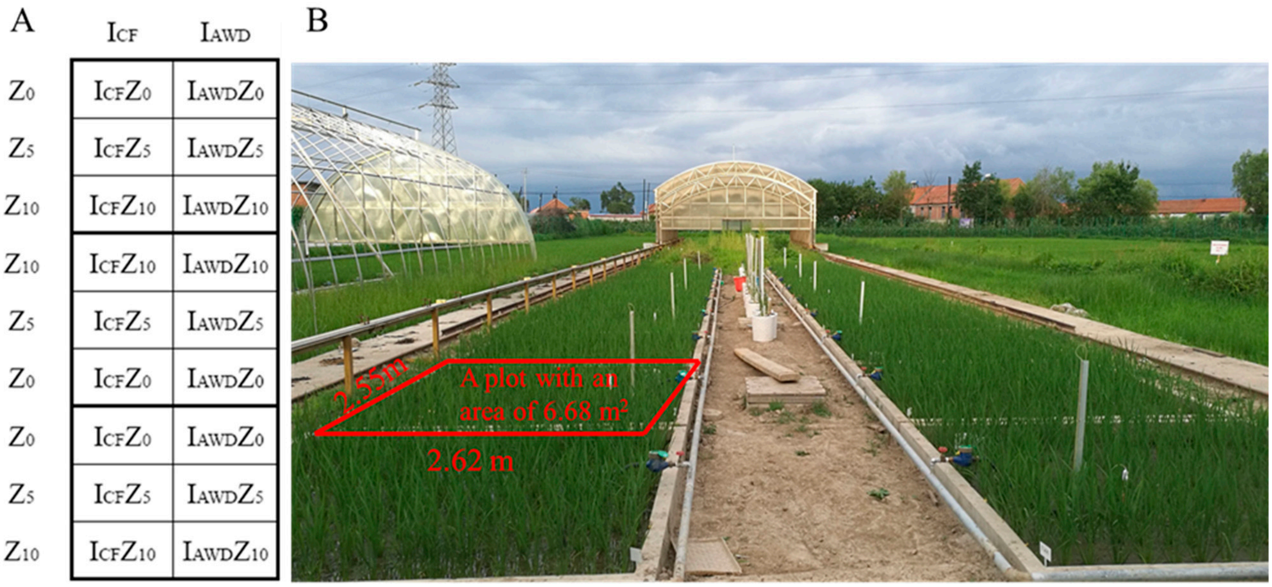

Figure 2. The experimental design (**A**) and layout (**B**) of split-plot experiment.

For the CF regime, a 1–5 cm water layer was maintained in the field during the whole rice-growing period, except for natural drying about 15 days before harvest. For the AWD regime, a 2–3 cm water layer was maintained in the field during the regreening stage, and then an alternating cycle of drying and wetting was conducted, the plots were irrigated to a water depth of 30–40 mm when the soil moisture was dry to −10~15 kPa, dried naturally about 15 days before harvest. The depth of water layer was monitored by water gauge at 8:00 am every day. The soil water potential at 15 cm depth was monitored by soil moisture tensiometers (Institute of Soil Science of Chinese Academy of Sciences, Nanjing, China) at 8:00 am and 2:00 pm every day. The amount of irrigation water was measured by a volumetric water meter installed on the irrigation pipe. In order to simulate deep leaching in the field, 1.5 mm d^{-1} of water was drained by a PVC pipe at soil depth of about 200 cm. Local fertilization standard was adopted. Nitrogen fertilizer (150 kg ha^{-1}) was applied in a ratio of 5:3:2 as base fertilizer (28 May), the first top dressing (10 June) and the second top dressing (21 July). Phosphate fertilizer (75 $kg \cdot ha^{-1}$) was applied as base fertilizer at one time; potassium fertilizer (60 $kg \cdot ha^{-1}$) was applied in a ratio of 5:5 as base fertilizer and the second top dressing. Zeolite was applied via surface application after soaking, and was incorporated into near-surface (0−5 cm) soil along with the base fertilizer at one time, which were mixed by turning over. Regular manual weeding was conducted to prevent weeds. Other cultivation techniques and field management followed local traditional methods. The row spacing of rice transplanting was 30 cm, the plant spacing was 14 cm and 3 plants were planted in each hole. The rice was transplanted on 28 May and harvested on 18 September.

2.3. Sampling and Measurements

2.3.1. Leaf SPAD and Root Bleeding Intensity

Leaf SPAD was measured by a chlorophyll meter (SPAD-502, Minolta Camera Co, Osaka, Japan) at tillering, joint-booting, panicle-initiation and grain-filling stages. A total of 3 representative plants with 3 uppermost fully expanded leaves were selected for measurement per treatment. Root bleeding intensity at the base was collected at a distance of 10 cm from the ground, absorbent cotton was used to absorb the bleeding fluid. Three holes of representative plants were selected for measurement per treatment at tillering, joint-booting, panicle-initiation and grain-filling stages; the measurement time was from 18:00 pm to 7:00 am the next day and root bleeding intensity was calculated from the weight difference of absorbent cotton before and after the measurement.

2.3.2. Dry Matter and Nitrogen Accumulation

At maturity, three holes of representative plants were selected for measuring dry matter and nitrogen accumulation per treatment. The samples were washed with distilled water and the root, stem, leaf and panicle were separated. The samples were placed in an oven at 105 °C for 30 min, and then adjusted to 80 °C for drying to constant weight. Dry matter accumulation was manually weighed by electronic scale. Root shoot ratio was calculated by the ratio of root dry weight to shoot dry weight.

2.3.3. Grain Yield and Water Use Efficiency

At maturity stage, each plot was harvested separately, then rice grain was naturally dried to a moisture content of about 14% to determine the yield. Water usage for each plot was calculated according to the principle of water balance. Water use efficiency was calculated using the following equation:

$$\mathrm{WUE} = \frac{Y}{W} \tag{1}$$

where Y is the grain yield ($\mathrm{kg \cdot ha^{-1}}$) and W is the total seasonal water use ($\mathrm{m^3 \cdot ha^{-1}}$).

2.3.4. Grain Quality

After harvesting, about 300 g of rice grains were taken from each treatment and air-dried for about 60 days for rice grain quality determination. The rice grain was hulled with an FC-2K Husker (Yamamoto, Japan) to obtain brown rice and brown rice rate was calculated by dividing that brown rice weight by rice grain weight. Brown rice was reprocessed by VP-32T Whitener (Yamamoto, Japan) to obtain milled rice and milled rice rate was calculated by dividing that milled rice weight by rice grain weight. Rice appearance quality (head rice rate, chalky rice rate and chalkiness degree) were measured by a ES-1000 Rice Inspector (Shizuoka, Japan). Protein concentration, amylose concentration and eating score were determined using a Infratec$^{\mathrm{TM}}$ 1241 Grain Analyzer (Foss, Tecator, Japan). Rice flour was obtained using a JFS-13A Tornado Crush Mill and a 3 g sample was mixed with 25 mL distilled water to determine starch viscosity properties. Starch viscosity properties (peak viscosity, through viscosity, breakdown, final viscosity, setback, peak time and pasting temp) were measured using a RVA-4 Rapid Visco Analyzer (Newport Scientific, Australia). The eating score was determined by a 1241 near infrared rapid quality analyzer (Foss, Tecator, Japan).

3. Result

3.1. Leaf SPAD and Root Bleeding Intensity

The changes in the leaf SPAD value and root bleeding intensity in different growth stages are shown in Table 2. The leaf SPAD value was the highest at the tillering stage due to the application of tillering fertilizer, and then there was a decreasing trend with the consumption of nitrogen in soil. The leaf SPAD value then increased gradually from the joint-booting to panicle-initiation stage, because the nitrogen in the soil was replenished again after the topdressing of panicle fertilizer, then tended to stabilize at the grain-filling stage. The irrigation regime only had a significant effect on the SPAD value at the grain-filling stage, AWD decreased the SPAD value by 5.0% at this stage compared with CF. Z addition significantly affected the SPAD value at the joint-booting and panicle-initiation stages. Compared with no Z addition, the application of 5 and 10 $\mathrm{t \cdot ha^{-1}}$ Z increased the SPAD value by 4.7% and 7.2% at the joint-booting stage, respectively. At the panicle-initiation stage, the application of 10 $\mathrm{t \cdot ha^{-1}}$ Z improved the SPAD value by 4.0%, but no significant difference was found between the Z_0 and Z_5.

Table 2. Effects of irrigation regimes and Z application rates on leaf SPAD and root bleeding intensity at different rice-growing stages.

Main Effect	Leaf SPAD Value				Root Bleeding Intensity ($g{\cdot}h^{-1}$)			
	Tillering Stage	Joint-Booting Stage	Panicle-Initiation Stage	Grain-Filling Stage	Tillering Stage	Joint-Booting Stage	Panicle-Initiation Stage	Grain-Filling Stage
I_{CF}	45.3 a	42.1 a	43.9 a	44.0 a	6.24 a	7.01 a	6.13 a	5.90 a
I_{AWD}	45.5 a	41.3 a	43.1 a	41.8 b	5.11 a	6.68 a	4.73 b	4.52 b
Z_0	44.8 a	40.1 c	42.6 b	42.5 a	5.49 a	6.37 b	5.04 b	4.74 b
Z_5	45.6 a	42.0 b	43.6 ab	42.9 a	5.70 a	6.88 ab	5.53 a	5.29 a
Z_{10}	45.9 a	43.0 a	44.3 a	43.2 a	5.85 a	7.31 a	5.71 a	5.59 a
ANOVA								
I	ns	ns	ns	*	ns	ns	**	**
Z	ns	**	**	ns	ns	**	**	**
I*Z	ns	ns	ns	ns	ns	ns	ns	ns

Notes: Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey's HSD test. *, ** and ns represent significance at $p < 0.05$, 0.01 and not significant. I: irrigation regime; Z: clinoptilolite zeolite application.

The root bleeding intensity increased first and then decreased during the whole rice-growing stage, and reached a peak at the joint-booting stage. The root bleeding intensity was not affected by the interaction effect of the irrigation regime and Z addition at all the observation stages. The irrigation regime had a significant effect on the root bleeding intensity at the panicle-initiation and grain-filling stages. Compared with CF, AWD reduced root bleeding intensity by 22.8% and 23.4% at the panicle-initiation and grain-filling stages, respectively. Z addition had a significant effect on the root bleeding intensity from the joint-booting to grain-filling stages. Compared with no Z addition, 10 $t{\cdot}ha^{-1}$ Z amendment increased the root bleeding intensity by 14.8% at the joint-booting stage. The application of 5 and 10 $t{\cdot}ha^{-1}$ Z improved the root bleeding intensity by 9.72% and 13.3% at the panicle-initiation stage, improved the root bleeding intensity by 11.6% and 17.9% at the grain-filling stage, respectively, relative to no Z addition, but no significant difference occurred between Z_5 and Z_{10}.

3.2. Dry Matter Accumulation and Distribution at Maturity Stage

The effect of irrigation regime and Z amendment on the dry matter accumulation and distribution at the maturity stage are shown in Table 3. The interaction between the irrigation regime and Z amendment had no significant effect on the dry matter accumulation and distribution proportion at the maturity stage. The irrigation regime had a significant effect on the dry matter accumulation in the stem-leaf and the dry matter distribution proportion in root and root–shoot ratio. Compared with CF, AWD reduced the dry matter accumulation in the stem-leaf by 6.9%, but had no significant effect in other tissues. AWD improved the proportion of dry matter distribution in root and root–shoot ratio by 11.0% and 11.2%, respectively, relative to CF.

Z amendment had a significant effect on the dry matter accumulation in different parts of the plant and the proportion of dry matter distribution in the stem-leaf and panicle. Compared with Z_0, Z_5 and Z_{10} improved the dry matter accumulation in the stem-leaf and panicle by 17.6% and 25.9%, and 8.9% and 13.5%; Z_5 and Z_{10} increased the aboveground dry matter accumulation by 13.1% and 18.7%, increased the total dry matter accumulation by 12.7% and 18.4%, respectively, and there was no significant difference between Z_5 and Z_{10}. Compared with Z_0, Z_5 and Z_{10} improved the dry matter distribution proportion in the stem-leaf by 4.2% and 6.5%, reduced the dry matter distribution proportion in the panicle by 2.7% and 4.4%, respectively, and there was no significant difference between Z_5 and Z_{10}.

Table 3. Effects of irrigation regimes and Z application rates on dry matter accumulation and distribution at maturity stage.

Main Effect	**Dry Matter Accumulation (kg·ha^{-1})**					**Dry Matter Distribution (%)**			
	Root	**Stem-Leaf**	**Panicle**	**Aboveground**	**Whole Plant**	**Root**	**Stem-Leaf**	**Panicle**	**Root–Shoot Ratio**
I_{CF}	6.10 a	30.3 a	38.2 a	68.5 a	74.6 a	8.17 b	40.5 a	51.3 a	0.089 b
I_{AWD}	6.48 a	28.2 b	36.9 a	65.1 a	71.6 a	9.07 a	39.2 a	51.7 a	0.099 a
Z_0	5.79 b	25.5 b	34.9 b	60.4 b	66.2 b	8.77 a	38.5 b	52.7 a	0.096 a
Z_5	6.33 ab	30.0 a	38.3 a	68.3 a	74.6 a	8.49 a	40.2 a	51.3 b	0.093 a
Z_{10}	6.74 a	32.1 a	39.6 a	71.7 a	78.4 a	8.60 a	41.0 a	50.4 b	0.094 a
ANOVA									
I	ns	*	ns	ns	ns	**	ns	ns	**
Z	**	**	**	**	**	ns	**	**	ns
I*Z	ns	ns	ns	ns	ns	ns	ns	ns	ns

Notes: Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey's HSD test. *, ** and ns represent significance at $p < 0.05$, 0.01 and not significant.

3.3. Nitrogen Accumulation and Distribution at Maturity Stage

The effect of the irrigation regime and Z amendment on nitrogen accumulation and distribution at maturity stage are shown in Table 4. Nitrogen (N) accumulation and distribution was not significantly affected by the interaction between the irrigation regime and Z amendment. The irrigation regime had a significant effect on N accumulation in the root, stem-leaf and aboveground parts, and the proportion of N distribution in the root and stem-leaf.

Table 4. Effects of irrigation regimes and Z application rates on nitrogen accumulation and distribution at maturity stage.

Main Effect	**N Accumulation (kg·ha^{-1})**					**N Distribution (%)**		
	Root	**Stem-Leaf**	**Panicle**	**Aboveground**	**Whole Plant**	**Root**	**Stem-Leaf**	**Panicle**
I_{CF}	8.84 b	28.0 a	78.4 a	106.4 a	115.3 a	7.66 b	24.2 a	68.1 a
I_{AWD}	9.69 a	24.7 b	76.1 a	100.6 b	110.3 a	8.63 a	22.3 b	69.1 a
Z_0	8.36 c	22.7 c	71.5 b	94.1 b	102.5 b	8.07 a	22.1 b	69.8 a
Z_5	9.39 b	27.0 b	78.7 a	105.6 a	115.0 a	8.06 a	23.5 a	68.5 a
Z_{10}	10.05 a	29.3 a	81.6 a	110.9 a	121.0 a	8.31 a	24.2 a	67.5 a
ANOVA								
I	*	*	ns	*	ns	**	*	ns
Z	**	**	**	**	**	ns	**	ns
I*Z	ns	ns	ns	ns	ns	ns	ns	ns

Notes: Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey's HSD test. *, ** and ns represent significance at $p < 0.05$, 0.01 and not significant.

Compared with CF, AWD significantly increased the root N accumulation by 9.6%, reduced the stem-leaf and aboveground N accumulation by 11.8% and 5.5%, improved the proportion of N distribution in the root by 12.7% and reduced the proportion of N distribution in the stem-leaf by 7.9%, respectively.

The N accumulation in different parts of the plants, and the N distribution ratio in the stem-leaf, were significantly affected by Z amendment. Compared with no Z addition, the addition of 5 and 10 t·Z ha^{-1} improved N accumulation in the root, stem-leaf, panicle, aboveground parts and whole pant by 12.3% and 20.2%, 18.9% and 29.1%, 10.1% and 14.1%, 10.9% and 15.1% and 12.2% and 18.0%, respectively, but no significant difference between Z_5 and Z_{10} occurred for N accumulation in the panicle, aboveground parts and whole plant. The application of 5 and 10 t·Z ha^{-1} improved the propoertion of N distribution in the stem-leaf by 6.3% and 9.5%, respectively, but no significant difference between Z_5 and Z_{10} occurred.

3.4. Grain Yield and Water Use Efficiency

Rice grain yield and water use efficiency were significantly affected by Z amendment and I*Z interaction (Figure 3). The water use efficiency was significantly affected by the irrigation regime's main effect, but this did not occur in the rice grain yield. In the condition of 0 and 5 t·Z ha^{-1} application, the rice grain yield was significantly reduced under AWD, relative to CF, but there was no significant difference between CF and AWD when 10 t·Z ha^{-1} was applied. Under CF, the addition of 5 and 10 t·Z ha^{-1} improved the grain yield by 6.4% and 6.5% and, under AWD, the addition of 5 and 10 t·Z ha^{-1} improved the grain yield by 7.8% and 12.8%, relative to no Z addition. The highest grain yields were obtained in the $I_{CF}Z_5$, $I_{CF}Z_{10}$ and $I_{AWD}Z_{10}$ treatments, and no significant difference among them occurred.

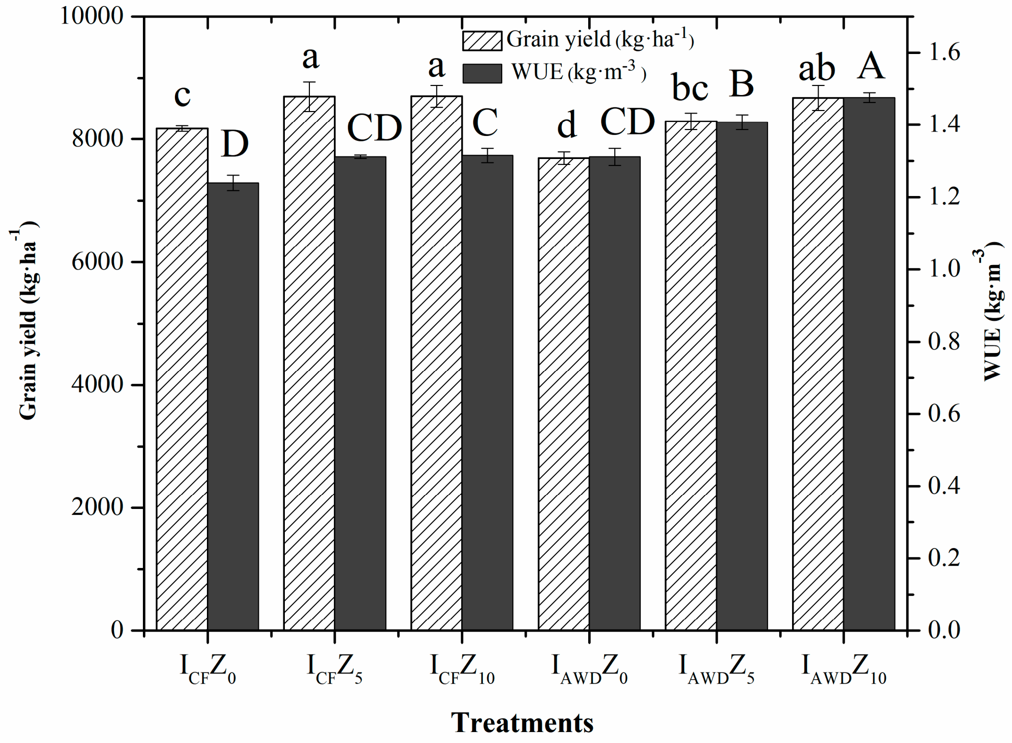

Figure 3. Rice grain yield and water use efficiency under different treatments. Different letters on the top of bars indicate significant difference at $p < 0.05$ between variables within the same group.

Compared with CF, AWD significantly improved the water use efficiency by 8.5%. Under CF, the addition of 5 and 10 t·Z ha^{-1} improved the water use efficiency by 5.6% and 6.5%. Under AWD, the addition of 5 and 10 t·Z ha^{-1} improved the water use efficiency by 7.6% and 12.2%, relative to no Z addition. The highest water use efficiency was obtained in the $I_{AWD}Z_{10}$ treatment; it improved the water use efficiency by 19.4% relative to $I_{CF}Z_0$ (the traditional cultivation mode).

The rice grain yield had a significant positive correlation with the aboveground dry matter accumulation, nitrogen accumulation, SPAD and root bleeding intensity at the joint-booting, panicle initiation and grain filling stages, especially with the aboveground dry matter accumulation, nitrogen accumulation, and SPAD at the joint-booting stage, but had a significant negative correlation with root–shoot ratio (Table 5). Nitrogen accumulation had a very significant correlation with dry matter accumulation; both of them were positively correlated with SPAD and root bleeding intensity, especially at the joint-booting stage. SPAD was positively correlated with root bleeding intensity.

Table 5. Correlation analysis among grain yield, root–shoot ratio, aboveground dry matter accumulation, aboveground nitrogen accumulation, SPAD and root bleeding intensity at joint-booting, panicle initiation and grain filling stages.

	Yield	**RST**	**ADM**	**AN**	**JBS**	**PIS**	**GFS**	**JBR**	**PIR**	**GFR**
Yied	1									
RST	−0.56 *	1								
ADM	0.88 **	−0.39	1							
AN	0.89 **	−0.46 *	0.99 **	1						
JBS	0.90 **	−0.44	0.86 **	0.86 **	1					
PIS	0.65 **	−0.4	0.68 **	0.71 **	0.77 **	1				
GFS	0.53 *	−0.83 **	0.52 *	0.55 *	0.53 *	0.53 *	1			
JBR	0.69 **	−0.35	0.81 **	0.82 **	0.63 **	0.53 *	0.48 *	1		
PIR	0.65 **	−0.80 **	0.57 *	0.61 **	0.57 *	0.53 *	0.88 **	0.59 **	1	
GFR	0.66 **	−0.76 **	0.59 **	0.63 **	0.63 **	0.67 **	0.85 **	0.53 *	0.95 **	1

Notes: RST, ADM, AN, JBS, PIS, GFS, JBR, PIR, GFR represent root–shoot ratio, aboveground dry matter accumulation, aboveground nitrogen accumulation, SPAD and root bleeding intensity at joint-booting, panicle initiation and grain filling stages, respectively. * and ** represent significance at $p < 0.05$, 0.01.

3.5. Grain Quality

The rice grain quality was not significantly affected by the interaction of the irrigation regime and Z amendment. The effects of the irrigation regime and Z amendment on the milling, appearance, nutritional and eating quality of rice grain are shown in Table 6. The irrigation regime had no significant effect on the brown rice rate, milled rice rate and chalkiness, but a significant difference in the head rice rate and chalky rice rate were noted between CF and AWD. AWD reduced the head rice rate by 4.7% and the chalky rice rate by 5.0%, relative to CF. Z application had no significant effect on the brown rice rate, milled rice rate and head rice rate, but a significant difference in the chalky rice rate and chalkiness were noted when Z was applied. Compared with no Z application, the addition of 10 t·Z ha^{-1} improved the chalky rice rate by 14.3% and the addition of 5 and 10 t·Z ha^{-1} increased the chalkiness by 15.0% and 35.2%, respectively.

Table 6. Effect of irrigation regimes and zeolite application on milling, appearance, nutritional and eating quality of rice grain.

Main Factor	**Brown Rice Rate (%)**	**Milled Rice Rate (%)**	**Head Rice Rate (%)**	**Chalky Rice Rate (%)**	**Chalkiness Degree (%)**	**Protein Concentration (%)**	**Amylose Concentration (%)**	**Eating Score**
ICF	84.3 a	78.3 a	73.1 a	6.41 a	1.43 a	6.62 a	25.2 a	69.4 b
IAWD	84.0 a	76.4 a	69.7 b	6.09 b	1.34 a	6.95 a	26.3 a	70.8 a
Z_0	84.2 a	76.8 a	70.5 a	5.82 b	1.20 c	6.52 b	25.8 a	70.4 a
Z_5	84.1 a	76.6 a	71.8 a	6.28 ab	1.38 b	6.77 ab	25.8 a	70.3 a
Z_{10}	84.2 a	78.8 a	71.8 a	6.65 a	1.59 a	7.00 a	25.6 a	69.7 a
ANOVA								
I								
Z	ns	ns	ns	**	**	*	ns	ns
I*Z	ns	ns	ns	ns	ns	ns	ns	ns

Notes: Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey's HSD test. *, ** and ns represent significance at $p < 0.05$, 0.01 and not significant.

The irrigation regime had no significant effect on the protein concentration and amylose concentration, but a significant difference in the eating score was found between CF and AWD. AWD significantly improved the eating score relative to CF. Z application had no significant effect on the amylose concentration and eating score, but a significant difference in the protein concentration was noted when Z was applied. The addition of 10 t·ha^{-1} Z increased the protein content by 7.4%, relative to no Z addition.

The effect of the irrigation regime and Z amendment on the starch RVA profile characteristics of the rice grain are shown in Table 7. The irrigation regime and Z amendment both had a significant effect on the breakdown and setback, but such a significant effect did not occur in the peak viscosity, through viscosity, final viscosity, peak time and pasting temp. AWD increased the breakdown by 5.9% and decreased the setback by 6.0%, relative to CF. Compared with no Z amendment, 5 and 10 t·ha^{-1} Z application both reduced the breakdown by 4.3% and 10 t·ha^{-1} Z application decreased the setback by 4.3%.

Table 7. Effect of irrigation regimes and zeolite application on starch RVA profile characteristics of rice grain.

Main Factos	Peak Viscosity (cP)	Through Viscosity (cP)	Breakdown (cP)	Final Viscosity (cP)	Setback (cP)	Peak Time (min)	Pasting Temp (°C)
I_{CF}	3159 a	2390 a	748 b	3518 a	1173 a	6.63 a	71.2 a
I_{AWD}	3218 a	2454 a	792 a	3557 a	1103 b	6.63 a	71.2 a
Z_0	3208 a	2416 a	793 a	3537 a	1164 a	6.62 a	71.3 a
Z_5	3160 a	2407 a	759 b	3520 a	1136 ab	6.65 a	71.1 a
Z_{10}	3208 a	2444 a	759 b	3555 a	1114 b	6.62 a	71.2 a
ANOVA							
I	ns	ns	*	ns	*	ns	ns
Z	ns	ns	**	ns	*	ns	ns
I*Z	ns	ns	ns	ns	ns	ns	ns

Notes: Means followed by the same letter within the same column are not significantly different at $p < 0.05$ by Tukey's HSD test. *, ** and ns represent significance at $p < 0.05$, 0.01 and not significant.

4. Discussion

4.1. Effects of AWD on Rice Physiological Characteristics, Yield and Water Use Efficiency

Although the water-saving effect of AWD is significant, there is still no consistent conclusion regarding its effects on rice physiological characteristics and grain yield. Crop roots are the main organ for absorbing nutrients and water; the present study also found that the rice root bleeding intensity was positively correlated with the grain yield (Table 5). Moderate drought stress significantly improved the rice root vigor, and then improved the grain yield, while severe drought stress had opposing effects [25]. In our study, AWD significantly reduced the root bleeding intensity at the grain filling stage (Table 2); although the drought stress was not severe, the main reason for this result was that the sustained low temperature at the panicle-initiation stage prolonged the drought stress duration, which inhibited the growth of the rice roots at a later stage. The leaves played two important roles in the rice-growing stage; on the one hand, they were the "source" organs for grain filling and, on the other hand, they were essential for dry matter production and the subsequent grain yield [26]. In the present study, AWD significantly reduced the SPAD at the grain filling stage, relative to CF; the main reason for this lower SPAD was that nutrient supply was inhibited due to the lower root bleeding intensity under AWD. A correlation analysis also indicated that the leaf SPAD was positively correlated with the root bleeding intensity (Table 5). Therefore, the lower root bleeding intensity and leaf SPAD would inhibit rice growth and development, which resulted in a significantly lower grain yield under AWD than CF without zeolite application in the present study.

As shown in a previous study [27–29], the rice grain yield was positively correlated with the aboveground dry matter accumulation (Table 5). The previous study found that the irrigation regime had no significant effect on the aboveground dry matter accumulation and yield [30]. Another study found that the aboveground dry matter accumulation under AWD treatment was significantly lower than that of CF before the grain filling stage, but that AWD significantly improved the dry matter accumulation and the subsequent grain yield at maturity stage [31]. In our study, the difference in the dry matter accumulation at maturity stage was not significant between CF and AWD (Table 3), which is the main reason that the grain yield was not significantly affected by the irrigation regime's main effect. One study examined 528 side-by-side comparisons of AWD with CF by meta-analysis; they found that mild AWD significantly improved the water productivity by an average of 24.2%, relative to CF [32]. The present study showed that AWD improved the water productivity by 8.5% (Figure 3), which was below average; this is ascribed to the fact that the yield of the AWD treatment was not higher than that of the CF and that AWD did not reduce water leakage due to the bottomed lysimeter used in this experiment.

4.2. Effects of AWD on Rice Grain Quality

Irrigation regime had a significant effect on the rice grain quality. Controlled irrigation, which is similar to the AWD used in our study, significantly improved the head rice rate [33]. Other studies also demonstrated the fact that water-saving irrigation can improve the head rice rate [34,35]. However, mild drought stress had no significant effect on the head rice rate, and severe drought stress significantly reduced the head rice rate [36]. In the present study, AWD significantly reduced the head rice rate of rice (Table 6). The main reason for this was that the grain filling was affected by prolonged drought stress in the AWD paddy due to the cold and humid climate during the panicle-initiation and grain-filling stages (Figure 1). In addition, our study showed that AWD significantly reduced the chalky rice rate and chalkiness degree, which concurred with previous published studies [33,34]; however, contrary to the research results of another study [37], these contradictory findings were mostly related to the different thresholds of water stress and rice varieties, etc.

Generally, rice with a high breakdown and a low setback is soft and sticky, and thus has a high taste quality [38]. The previous study indicated that the rice grain quality was improved when the soil-water potential was −15 kPa during the grain-filling stage [39]. In our study, the soil water potential of the AWD was −10 kPa in the present experiment, which significantly improved the eating score of the rice due to the higher breakdown and lower setback under AWD than CF. In conclusion, the effects of water-saving irrigation on rice quality are still unclear. Therefore, studies on the effects of water-saving irrigation on rice quality should be carried out simultaneously around multi-point experiments, multi-variety experiments and multiple water stress regimes.

4.3. Effects of Zeolite on Rice Physiological Characteristics, Yield and Water Use Efficiency

The application of zeolite to paddies could improve rice yield to varying degrees [20,40–42]. The present study also demonstrated that the addition of zeolite significantly improved the rice grain yield under both CF and AWD. Furthermore, the large specific surface area and high hydration–dehydration properties of zeolite enhanced the water-holding capacity for soil, especially under drought stress conditions, which was beneficial in offsetting the negative effects of drought stress on rice growth and subsequent yield [43]. Our study showed that the grain yield increased significantly with the increase in Z addition rate under AWD; similar conclusions were found in previously published studies [23,44,45]. In addition, the application of Z enhanced root bleeding intensity, mainly because of the enhanced the availability of nutrients in the soil by Z amendment, which, in turn, increased the leaf SPAD in our study (Table 2), delayed leaf senescence and promoted nitrogen accumulation in plants. The higher root vigor at the grain-filling stage is closely related to the synthesis of phytohormones, especially cytokinins, which help to regulate photosynthesis and then promote dry matter accumulation [46]. Rice physiological characteristics, dry matter and nitrogen accumulation are closely related to rice yield (Table 5). Therefore, the mechanism of increasing the yield via Z application could be explained by the fact that Z promoted the dry matter and nitrogen accumulation by improving the physiological function of rice. Additionally, the increase in nitrogen accumulation by zeolite might be due to its large specific surface area and high nitrogen exchange ability.

Zeolite application could significantly improve crop water use efficiency [20]. In the present study, the water use efficiency improved significantly with the increase in Z addition rate; this could be attributed to the fact that Z application significantly increased the rice yield without increasing the water consumption. Additionally, the water saving effect of zeolite was more significant under AWD. Therefore, the application of 10 t·ha^{-1} Z could offset the adverse effects of yield reduction, further improve the water use efficiency and achieve the win–win goal of increasing yield and saving water in the AWD paddy field, which is of great significance for the promotion of the AWD cultivation regime.

4.4. Effects of Zeolite on Rice Grain Quality

Rice grain quality is closely related to cultivation measures. For example, increasing nitrogen fertilizer application could reduce the chalky rice rate and chalkiness degree, and thus improve the appearance quality of rice [10], which is consistent with another study [47]. However, some studies obtained the opposite results and found that an increasing rate of nitrogen fertilizer addition significantly increased the chalky rice rate and chalkiness degree [35,48]. The above studies showed that nitrogen fertilizer management is one of the main factors affecting rice quality. Therefore, zeolite could affect rice grain quality by improving the nitrogen and water availability in soil. A study found that Z had no significant effect on the appearance quality of rice [49], but another study showed that Z application reduced the chalky rice rate and chalkiness [50]. In the present study, Z application significantly increased the chalky rice rate and chalkiness degree (Table 6). The formation of chalkiness is closely related to the level of "source-sink" during the grain filling stage, so the main reason for increasing chalkiness with Z amendment might be that an increased "sink" and insufficient "source" of rice resulted in more chalkiness during the grain-filling stage due to the higher nitrogen proportion in the second topdressing. In line with our finding, a high addition rate of nitrogen fertilizer during the panicle-initiation stage increased the chalkiness degree of rice [35]. Our study found that zeolite application improved the protein concentration in rice grain; this finding is mostly related to promoting the absorption and utilization of nitrogen in plants due to the fertilizer retention properties by zeolite amendment. In the present study, although zeolite application improved the protein concentration, it did not affect the amylose concentration, nor did it reduce the eating score. Zeolite application reduced both the breakdown and setback (Table 7), which may be one of the reasons why it did not reduce eating score. To sum up, the effect of zeolite on rice grain quality should be further explored, in combination with different nitrogen dosages and application methods. These results indicated that the integration of AWD with 10 t·Z ha^{-1} addition could be an effective approach for enhancing rice grain yield and quality with high water use efficiency.

5. Conclusions

AWD significantly reduced the root bleeding intensity and leaf SPAD, increased the root–shoot ratio, reduced the aboveground N accumulation and resulted in a lower rice grain yield without zeolite application, relative to CF. Zeolite amendment significantly improved the rice grain yield by improving the root bleeding intensity, leaf SPAD, dry matter and subsequent N accumulation. Both AWD and zeolite amendment significantly improved the water use efficiency. Compared with CF, although AWD reduced the head rice rate, it improved the appearance quality by reducing the chalkiness, and improved eating score by increasing the breakdown and reducing the setback. Zeolite amendment improved the chalkiness and protein concentration. Zeolite amendment reduced both the breakdown and setback, resulting in no significant effect on the rice amylose concentration and eating score. In general, the integration of 10 t·Z ha^{-1} with AWD improved the rice grain yield and grain quality with an increased water use efficiency. Furthermore, the impact of modified zeolite on crop yield and quality deserves attention in future research.

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