Effects of zeolite application on grain yield, water use and nitrogen uptake of rice under alternate wetting and drying irrigation

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Abstract: With the increasing scarcity of water resources and growing population, the dual goal of saving irrigation water and increasing grain yield has become a major challenge in rice production around the world. A two-year lysimetric experiment was conducted to assess the effects of zeolite application (Z_0: 0 and Z_1: 15 t/hm^2) and water regimes (W_0: continuous flooding irrigation, W_1: energy-controlled irrigation, W_2: alternate wetting and drying irrigation) on grain yield, water use and total nitrogen uptake of rice. Zeolite addition to paddy field significantly increased grain yield, total N uptake, and water use efficiency (WUE), despite a negligible effect on amount of irrigation water used. Compared with W_0, the separate use of W_1 and W_2 each considerably decreased irrigation water. However, W_2-grown rice showed a significant decline in grain yield. In contrast, W_1 showed comparable grain yield with W_0, and achieved the highest WUE. Correlation analysis revealed that grain yield was significantly and positively correlated with effective panicles, spikelets per panicle, water consumption, and total N uptake. It is concluded that the combination of zeolite application at the rate of 15 t/hm^2 and energy-controlled irrigation could be recommended to benefit farmers by reducing irrigation water while improving grain yield on a clay loam soil.

Keywords: zeolite, alternate wetting and drying irrigation, rice, yield, water use efficiency
DOI: 10.25165/j.ijabe.20181101.3064

Citation: Zheng J L, Chen T T, Xia G M, Chen W, Liu G Y, Chi D C. Effects of zeolite application on grain yield, water use and nitrogen uptake of rice under alternate wetting and drying irrigation. Int J Agric & Biol Eng, 2018; 11(1): 157–164.

1 Introduction

In order to cope with the increasing water scarcity, a number of water-saving methods have been developed to decrease irrigation water and improve water use efficiency in rice production system, such as saturated soil culture[1], aerobic rice[2], system of rice intensification[3], non-flooded mulching cultivation[4], alternate wetting and drying irrigation (AWD)[5,6], etc. Among these methods, AWD is the most widely used worldwide, especially in China. In AWD treatment, the field does not need to be kept submerged all the time but is allowed to dry out to some degree when soil water potential reach –10 kPa to –30 kPa before it is re-flooded during the whole rice growing season[7,8]. Many studies have demonstrated that AWD could indeed save irrigation water and improve water use efficiency compared with traditional flood irrigation[5,8,9], but the effect of AWD on rice yield was still in debate. Some studies have shown that the adoption of AWD could maintain[9] or even increase rice yield[10]. While Bouman and Tuong[5] summarized 31 published researches on AWD and concluded that 92% of the AWD treatments lead to yield decrease compared with continuously flooded treatment. Whether AWD could obtain the win-win goal of saving irrigation water and increasing rice grain yield is still a challenge faced by most researchers[11]. In many studies, the threshold of AWD was set as a fixed value during the whole rice growing season; this may cause rice to suffer from drought stress when it comes to the key water requirement stage and eventually lead to yield reduction. It is reported that rice yield reductions occurred ranging from 10%-40% when soil water potentials at 10-20 cm depth reached –10 kPa to –30 kPa before the field was reflooded[5]. Wiangsamut[12] reported a yield decline of more than 30% compared with continuous flood irrigation in Tarlac Province, Philippines, when soil water potential reached –30 kPa before the irrigation was applied. In some previous reports, the observed yield decline was resulted from the reduction in dry matter production, panicle and spikelet number, and 1000-grain weight when the thresholds were within a range from –20 kPa to –30 kPa[13,14]. Chi et al.[15] proposed a water-saving method in 2003, which called energy-controlled irrigation and farmers could achieve the dual goal of saving irrigation water and increasing rice yield. In energy-controlled irrigation, the threshold for irrigation is not constant, but is varied with the sensitivity of rice to water stress at specific growth stage.

The AWD may also impact grain yield through altering nitrogen cycle in rice system[16]. Under AWD irrigation, the soil is alternately submerged and non-submerged, which lead to aerobic and anaerobic conditions. During the aerobic period, ammonia nitrogen is prone to be nitrified due to the availability of oxygen in the soil. And the nitrification process provides nitrate nitrogen for denitrification when the soil is rewetting again[17]. Accordingly, the alternate wetting and drying cycle increased the nitrogen loss by accelerating nitrification-denitrification processes. The

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Received date: 2017-04-12 **Accepted date:** 2017-07-02

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nitrogen loss not only lead to low nitrogen use efficiency, but also cause serious environmental risk such as eutrophication, groundwater pollution, emission of greenhouse gases and so on[18]. In order to improve N use efficiency and increase rice yield, many N-saving techniques have been developed, i.e. N fertilizer split application, application of controlled-release N fertilizers, and adoption of soil amendments. Recently, zeolite has been widely used in agriculture as inorganic soil amendment to decrease N leaching, improve N use efficiency and increase crop yield. Zeolites are crystalline hydrated aluminosilicates materials, characterized by high cation exchange capacity, high adsorption capacity and water holding capacity which have promoted their widespread use in agriculture[19]. The high affinity of zeolite for plant nutrients especially NH_4^+ have made it to be used to improve soil nitrogen retention and nitrogen availability to plants. Zeolites have been reported to improve N use efficiency and increase yield of many crops such as spinach[20], canola[21], corn[22] and rice[23,24]. Although there were many studies about the effects of zeolite application on agronomic characters of rice under continuous flood irrigation, few studies have looked into its effect on rice under AWD. In addition, zeolite could also improve water use efficiency by increasing soil water retention capacity and water availability to plants[25]. Natural zeolites have been proved to increase crop water use efficiency[26]. Hazrati et al.[27] reported that zeolite application rate of 8 g/kg significantly increased Water use efficiency (WUE) of *A. vera* and obtained the highest value. Ozbahce et al.[28] found that the zeolite dose of 90 t/hm^2 and the irrigation levels at 100% ET obtained the highest WUE of common bean. Abdi et al.[29] reported that zeolite application increased the WUE of strawberry. Zeolite also has the capacity to retain water in itself and therefore increases the water availability to plant under water stress[30]. Hence, whether the combination of zeolite application and AWD irrigation could further reduce irrigation water, alleviate N loss, and increase rice grain yield should be confirmed and studied.

The objective of this study was to investigate the effect of zeolite application on rice grain yield, water use efficiency and total nitrogen uptake under alternate wetting and drying irrigation. It is hypothesized that the combination of zeolite and energy-controlled irrigation may increase rice yield, total N uptake, reduce water use and improve water use efficiency. Furthermore, the effect of zeolite application and water regimes on shoot and root dry weight, soil total nitrogen and cation exchange capacity (CEC) were also evaluated.

2 Materials and methods

2.1 Site description and materials

The experiment was conducted in non-weighing lysimeters at the Liaoning Provincial Key Station for Agricultural Irrigation Research, Shenyang, China (42°08′57″N, 120°30′45″E, 47 m altitude). The study area has a temperate continental monsoon climate with 7.5°C average annual air temperature. Average annual rainfall is 672.9 mm, with the main rainy season lasting from June to September. The soil of experimental field was a clay loam soil with organic matter of 22.30 g/kg, alkali hydrolysable N of 75.41 mg/kg, Olsen-P of 18.39 mg/kg, exchangeable K of 81.28 mg/kg, total N of 0.78 g/kg, total P of 0.48 g/kg, total K of 21.90 g/kg, and pH of 7.4 (soil/water, 1:2.5). The saturated soil water contents (v/v) is 42.2%, and bulk density of the soil is 1.50 g/cm.

Shennong 9765 (*Oryza sativa*. L), a predominant local middle-late season rice cultivar bred by the Rice Research Institute of Shenyang Agricultural University was used, which characterized by high yield, good quality and strong resistance to diseases[31]. The chemical fertilizer used were urea (46% N) as N fertilizer, superphosphate (12% P_2O_5) as P fertilizer, and potassium sulfate (50% K_2O) as K fertilizer, respectively. Zeolite (particle size between 0.18 mm and 0.38 mm) containing a high percentage of clinoptilolite was obtained from a quarry in Faku County, Liaoning Province, China. The chemical content of zeolite is listed in Table 1.

Table 1 Chemical content of zeolite

Chemical content	Percentage/%	Chemical content	Percentage/%
SiO_2	65.56	Na_2O	0.39
Al_2O_3	10.62	K_2O	2.87
Fe_2O_3	0.63	TiO_2	0.069
FeO	0.09	P_2O_5	0.001
MgO	0.82	MnO	0.01
CaO	2.59	Ignition loss	16.59
H_2O	8.16		

2.2 Experimental design

The experiment was laid out in a split-plot design with three replications during the rice growing season (from May to October) in 2014 and 2015. Zeolite amendment (Z_0: 0 and Z_1: 15 t/hm^2) was main plot. Zeolite application rate of 15 t/hm^2 in this study was recommended by Chen et al.[32], who reported that zeolite addition to paddy field at the rate of 10-15 t/hm^2 was the most effective to increase rice grain yield in the same province. Within each of these main plots, the sub-plots were subjected to three water regimes (W_0: continuous flooding irrigation; W_1: energy-controlled irrigation[15] and W_2: alternate wetting and drying irrigation). The lysimeter was 2.5 m × 2 m in size and had a depth of 1.8 m under an automatic rain shelter. The impact of rainfall was avoided using the automatic rain shelter to rigorously control the soil water content in the plot. Each plot was individually irrigated using a pipeline with a water meter installed. Zeolite was applied to the puddled plots and mixed into the soil by rake. In order to study the long-term effect of zeolite application, zeolite was only applied in the first year. In W_0 treatment, the fields were continually flooded with a 1-5 cm water level until one week before harvest. In both W_1 and W_2 treatment, the fields were kept flooded with a 3-5 cm and 1-3 cm water depth for the first 7-10 d after transplanting. Thereafter, W_1 and W_2 were managed differently. In W_1 treatment, the fields were left drying before reflooding base on the threshold of the soil water potentials in specific growth stage. While in W_2 treatment, the fields were left drying before reflooding until the soil water potentials reached to –15 kPa. The details for the three water regimes are listed in Table 2. In addition, when necessary farm work such as pesticide and fertilizer was applied, the plot must keep standing water for a few days.

Rice was seeded on 25 April in 2014 and 30 April in 2015, and transplanted at a hill spacing of 30 cm × 15 cm with four seedlings per hill on 20 May in 2014 and 24 May in 2015, respectively. Fertilizer management was based mainly on local farmers' practices. N as urea (210 kg N/hm^2) was applied in three parts: 43% as basal, 43% at tillering and 14% at panicle initiation. Potassium (75 kg K_2O/hm^2) was applied in two parts: 50% as basal and 50% at tillering. Phosphorus (60 kg P_2O_5/hm^2) was applied as basal dressing. Weeds, insects and diseases management were all in agreement with the local farmers' practices. No noticeable crop damage from weeds, insects and diseases was observed in the experiments in both years.

Table 2 Water management for different growth stages under continuous flooding, energy-controlled and alternate wetting and drying irrigations

Growth stages	W_0	W_1		W_2	
	Water depth /cm	Water depth /cm	Soil water potential /kPa	Water depth /cm	Soil water potential /kPa
Seedling recovery and initial tillering stage	1-5	5-3	0	1-3	0
Middle tillering stage	1-5	3-0	–5- –10	1-3	–15
Late tillering stage	1-5	0	–25- –35	1-3	–15
Jointing–booting stage	1-5	5-0	–5- –10	1-3	–15
Heading–flowering stage	1-5	5-0	–5- –10	1-3	–15
Milky ripening stage	1-5	3-0	–10- –20	1-3	–15
Yellow ripening stage	drying	drying	/	drying	/

Notes: W_0, W_1 and W_2 represent continuous flooding irrigation, energy-controlled irrigation, and alternate wetting and drying irrigation, respectively.

2.3 Measurements and calculations

Tensiometers (made by Institute of Soil Science of Chinese Academy of Sciences, Nanjing, China) were installed at W_1 and W_2 treatment plots to monitor the soil water potentials. It was measured daily at 8:00 and 14:00. Under W_1 and W_2 treatment, the plot was irrigated to the depths shown in Table 2, when the soil water potential reached the corresponding threshold for each specific growth stage. The volume of irrigation water was measured by the water meter installed in the irrigation pipeline. Water percolation was simulated by releasing 2.0 mm H_2O per day through the drainage system of the lysimeter. Each plot was irrigated and drained independently.

WUE, kg/m^3, was calculated as the ratio of grain yield to water consumption. Water consumption was calculated using Equation (1) as follow[32]:

$$W_T = P + I + K + (\theta_0 - \theta_Y) \tag{1}$$

where, W_T is crop water consumption, mm; P is precipitation, mm; I is total irrigation water amount, mm; K is groundwater recharge, mm; θ_0 and θ_Y is soil water storage of the plot before land soaking and after harvesting, respectively. Since the lysimeter is equipped with automatic rain shelter to avoid precipitation and has a closed bottom, P and K are both zero. The difference between θ_0 and θ_Y is calculated using Equation (2) as follow:

$$\theta_0 - \theta_Y = I_Y - I_0 \tag{2}$$

where, I_0 is the irrigation amount for land soaking to a water depth about 5 cm, and I_Y is the irrigation amount to obtain a water depth about 5 cm after harvesting, mm. WUE is calculated using Equation (3) as follow:

$$\text{WUE} = Y / W_T \tag{3}$$

where, WUE is water use efficiency, and Y is rice grain yield.

The crop was harvested manually on 19 and 17 September in 2014 and 2015, respectively. At physiological maturity, grain yield was measured from all the plants in each plot. The aboveground total biomass was measured before the harvest day. Three plants with representation of average tiller numbers in each plot (eliminating the border effects) were sampled randomly. The plants were cut at ground level and divided into three parts: stem, leaf and panicle. For measurement of root biomass, the roots in soil were dug out by a spade (30 cm in length × 15 cm in width × 20 cm in depth). The roots were rinsed and then air dried. All plant samples were oven-dried at 80°C for 48 h to constant weight and weighted. Plant samples were finely ground to pass a 0.15 mm sieve, and then subsamples were taken for N content determination. Tissue N content was determined by micro Kjeldahl digestion, distillation, and titration to calculate aboveground N uptake[33]. Aboveground total N uptake was computed from the sum of the dry matter and N concentration of the different plant parts. Plants were harvested by hand and threshed by a hand-driven thresher. Plants were air dried for about one week before grain yield being measured based on 14% moisture. Yield components including effective panicles, spikelets per panicle, grain filling percentage, and 1000-grain weight were measured from 5 plants which were sampled randomly from each plot (avoid border plants).

After harvesting, surface soil sample were collected with a hand auger from 0 to 30 cm depth at 3 locations for each plot to determine soil total nitrogen and cation exchange capacity (CEC). Soil total nitrogen was determined by Kjeldahl method[33]. And CEC values were determined by the ammonium acetate method[34].

2.4 Statistical analysis

All data (two-year average) were analyzed as a split-plot design by analysis of variances (ANOVA), using the SAS GLM procedure (SAS ver. 9.4). Mean value for the three replicates were computed for all traits. Treatment means were compared using Tukey's HSD tests at the 5% statistical probability level. Spearman's correlation analysis was used to reveal the correlated relationship among different traits.

3 Results

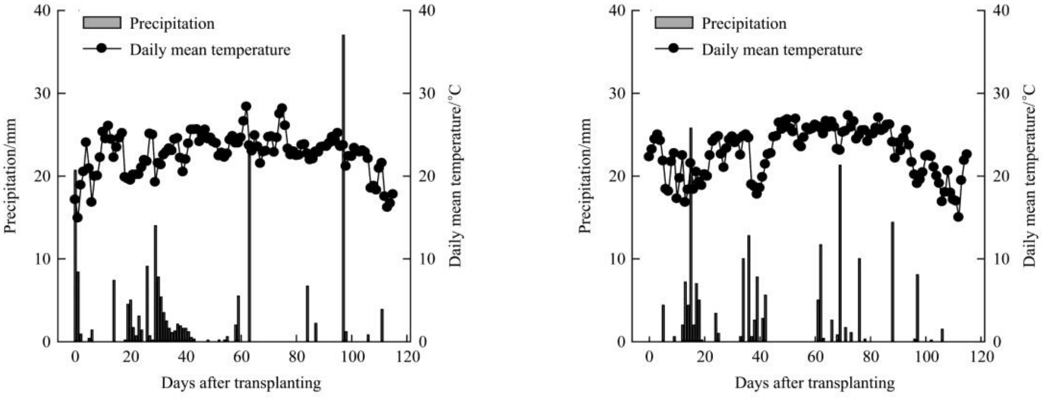
3.1 Growth conditions

Figure 1 shows the daily precipitation and mean temperature from transplanting to harvest in both years. The total precipitation was 231.7 mm in 2014 and 185.6 mm in 2015, respectively. Maximum daily precipitation was 37 mm at 25 August (97 DAT) in 2014 while was 25.8 mm at 8 June (15 DAT) in 2015. The daily mean temperature during the growth season increased firstly and then decreased in both years. Figure 2 shows the soil water potential measured at 15 cm depth in different water regimes during the whole growing season. It declared that the expected water treatments were achieved. In W_2 treatment, the fluctuation of soil water potential is within –15 kPa. And the threshold of soil water potential in W_1 treatment varied with the growth stage. When the soil water potential in a plot reached the corresponding threshold, the plot was irrigated, and the soil water potential increased suddenly. A lower soil water potential (reached to –25 kPa) occurred in W_1 treatment during the late tillering stage.

3.2 Shoot and root dry weight

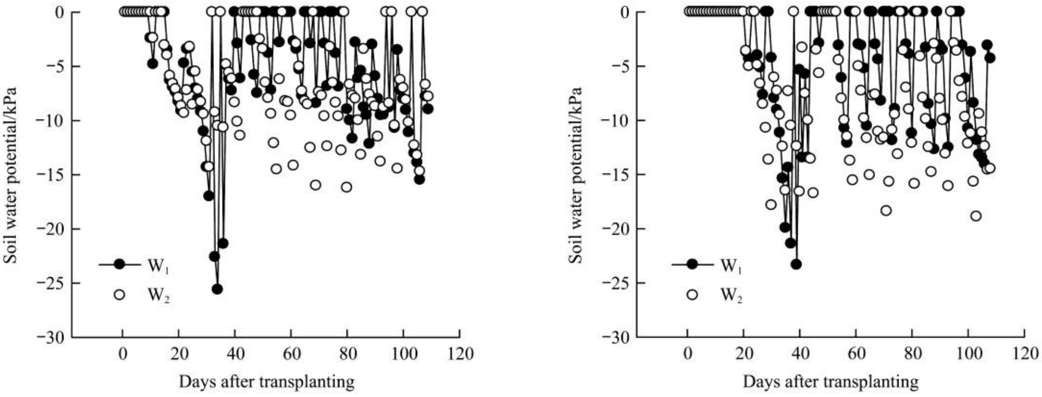
There were no significant interaction effects between zeolite application (Z) and water regimes (W) on shoot and root dry weight (Table 3). Zeolite application had a significant effect on spike and root dry weight (DW). Z_1 treatment significantly increased spike and root DWs by 10.8% and 18.5%, respectively, as compared to Z_0 (Table 4). This indicated that application of zeolite could improve the shoot and root growth which might be related to the retention of water and nitrogen by zeolite.

The effects of water regimes on leaf and spike DWs were highly significant ($p<0.01$). Compared with W_0 treatment, W_1 and W_2 significantly reduced leaf DW (Table 4). W_1 did not differ from W_2 in leaf DW, although a numerically higher leaf DW achieved compared to W_2. Spike DW was significantly decreased in W_2 treatment compared with W_0 or W_1 treatment. W_2 reduced spike DW by 15.8% as compared to W_0 treatment. And there was no significant difference between W_1 and W_0 treatment in spike DW. The highest root DW was obtained from W_0 treatment, followed by W_1 treatment, and W_2 treatment. However, the differences among them were insignificant.



a. 2014 b. 2015

Figure 1 Daily precipitation and mean temperature during the rice growing season in 2014 and 2015 in Shenyang, China



a. 2014 b. 2015

Figure 2 Soil water potential from transplanting to harvest of rice under different water regimes in 2014 and 2015

Table 3 Analysis of variance for DW of rice

Source of variation	df	MS			
		Stem DW	Leaf DW	Spike DW	Root DW
Block	2	0.04^{ns}	0.06^{ns}	0.20^{ns}	0.06^{ns}
Z	1	0.07^{ns}	0.01^{ns}	5.16^{*}	0.83^{*}
Error(z)	2	0.56	0.14	0.23	0.02
W	2	0.77^{ns}	0.43^{**}	5.98^{**}	1.21^{ns}
Z*W	2	0.48^{ns}	0.09^{ns}	0.48^{ns}	0.05^{ns}
Error(w)	8	0.30	0.02	0.19	0.33
CV (%)		9.24	6.29	4.19	22.78

Notes: *, ** and ns denote significant at the 5% and 1% probability levels and not significant, respectively. Z-zeolite application, W-water regimes, CV-coefficient of variance, DW-dry weight.

Table 4 Mean comparisons of zeolite and water regimes on DW of rice

Main effects	Stem DW/t·hm^{-2}	Leaf DW/t·hm^{-2}	Spike DW/t·hm^{-2}	Root DW/t·hm^{-2}
Zeolite application				
Z_0	5.99a	2.46a	9.94b	2.32b
Z_1	5.86a	2.47a	11.01a	2.75a
Water regimes				
W_0	6.07a	2.74Aa	11.07Aa	2.95a
W_1	6.19a	2.44Bb	11.04Aa	2.60a
W_2	5.52a	2.21Bb	9.32Bb	2.06a

Notes: In a column within the same factor, means followed by the same lowercase or capital letter are not significantly different at the 5% and 1% probability levels by Tukey's HSD tests, respectively. DW: dry weight.

3.3 Grain yield and yield components

Table 5 shows the ANOVA results of grain yield and yield components as affected by zeolite application and water regimes. No significant interaction effects between Z and W on grain yield, effective panicles, spikelets per panicle, grain filling percentage and 1000-grain weight were observed averaged over two years. Zeolite application had a significant effect on grain yield, effective panicles, and spikelets per panicle at the 5% probability level and 1000-grain weight at the 1% probability level (Table 5). The effect of zeolite application on grain filling percentage was insignificant. Water regimes had a significant influence on grain yield and effective panicles at the 1% probability level, but did not impact spikelets per panicle, grain filling percentage, and 1000-grain weight.

Table 5 Analysis of variance for yield and yield components of rice

Source of variation	df	MS				
		Grain yield	Effective panicles	Spikelets per panicle	Grain filling percentage	1000-grain weight
Block	2	0.18^{ns}	3.27^{ns}	5.93^{ns}	0.50^{ns}	0.08^{ns}
Z	1	2.52^{*}	1.78^{*}	1440.61^{*}	3.01^{ns}	0.72^{**}
Error(z)	2	0.08	0.08	49.48	0.19	0.01
W	2	5.28^{**}	24.82^{**}	150.95^{ns}	8.33^{ns}	0.03^{ns}
Z*W	2	0.10^{ns}	0.04^{ns}	122.27^{ns}	2.52^{ns}	0.04^{ns}
Error(w)	8	0.07	0.98	73.21	1.94	0.32
CV (%)		2.48	6.96	6.22	1.45	2.27

Notes: *, **, and ns denote significant at the 5% and 1% probability levels and not significant, respectively. Z: zeolite application, W: water regimes, CV: coefficient of variance.

Table 6 shows the mean comparisons of zeolite amendment and water regimes on grain yield and yield components. Zeolite addition at the rate of 15 t/hm^2 significantly increased grain yield by 7.5% compared with Z_0 treatment. Grain yield was also influenced by water regimes. The shift from W_0 to W_2 irrigation negatively affected grain yield, decreasing grain yield by up to 15.3%. However, the shift from W_0 to W_1 irrigation did not show a measurable difference in grain yield. Effective panicles, spikelets per panicle, and 1000-grain weight were all significantly increased with zeolite addition. Z_1 treatment increased effective panicles by 4.5%, spikelets per panicle by 13.9%, and 1000-grain weight by 1.6%, respectively, when compared with Z_0 treatment. Despite an increase trend was observed, the effective panicles under W_1 treatment did not differ from that under W_0 treatment. However, a significant decrease in effective panicles was detected under W_2 treatment. Compared with W_0 treatment, effective panicles under W_2 treatment was declined by 19.2%.

Table 6 Mean comparisons of zeolite and water regimes on yield and yield components of rice

Main effects	Grain yield/t·hm^{-2}	Effective panicles	Spikelets per panicle	Grain filling percentage/%	1000-grain weight/g
Zeolite levels					
Z_0	10.05b	13.89b	128.59b	96.35a	24.78Bb
Z_1	10.80a	14.52a	146.48a	95.53a	25.18Aa
Water regimes					
W_0	11.04Aa	14.78Aa	143.13a	94.64a	24.91a
W_1	10.89Aa	15.89Aa	136.01a	96.25a	24.98a
W_2	9.35Bb	11.94Bb	133.45a	96.94a	25.05a

Notes: In a column within the same factor, means followed by the same lowercase or capital letter are not significantly different at the 5% and 1% probability levels by Tukey's HSD tests, respectively.

3.4 Total N uptake, soil total nitrogen and CEC

Table 7 shows the ANOVA results of water consumption, WUE, soil total nitrogen, CEC and total N uptake as influenced by zeolite application and water regimes. The interaction effects between Z and W on total N uptake, soil total nitrogen, and cation exchange capacity (CEC) were non-significant (Table 7). Zeolite application had a significant effect on soil total nitrogen and total N uptake at the 5% probability level and CEC at the 1% probability level, respectively. Water regimes had no significant effect on these traits.

Table 7 Analysis of variance for water consumption, WUE, soil total nitrogen, CEC and total N uptake of rice

Source of variation	df	MS				
		Water consumption	WUE	Soil total nitrogen	CEC	Total N uptake
Block	2	1470.3371^{ns}	0.0050^{ns}	0.0074^{ns}	0.1511^{ns}	124.8449^{ns}
Z	1	1966.4811^{ns}	0.0593*	0.0355*	10.9041**	2646.9951*
Error(z)	2	460.1971	0.0025	0.0012	0.0332	119.4197
W	2	85505.7921**	0.0582**	0.0115^{ns}	0.7670^{ns}	148.5346^{ns}
Z×W	2	5785.3681*	0.0258**	0.0046^{ns}	0.0295^{ns}	99.6779^{ns}
Error(w)	8	1070.4920	0.0028	0.0042	0.6646	45.5913
CV (%)		4.0316	4.0867	8.5952	4.9189	8.3939

Notes: *, ** and ns denote significant at the 5% and 1% probability levels and not significant, respectively. WUE and CEC represent water use efficiency and cation exchange capacity, respectively. Z: zeolite application, W: water regimes, CV: coefficient of variance.

Table 8 shows the mean comparisons of zeolite application and water regimes on water consumption, WUE, soil total nitrogen, CEC and total N uptake. Soil total nitrogen under Z_1 treatment was 0.80 g/kg, significantly higher than that under Z_0 treatment with 0.71 g/kg (Table 8). Water regimes did not alter the soil total nitrogen at the $p<0.05$ significant level. Total N uptake was significantly affected by application of zeolite. Zeolite addition at the rate of 15 t/hm^2 increased total N uptake by 35.5%. Comparing the water regimes, total N uptake was the highest under W_0 treatment, and intermediate under W_1 treatment, and the lowest under W_2 treatment, while the differences among them were insignificant. The topsoil CEC was significantly influenced by zeolite addition. Zeolite addition increased CEC by 9.8% as compared to the zero-zeolite control. Water regimes did not show a significant difference in CEC at the $p<0.05$ significant level.

Table 8 Mean comparisons of zeolite and water regimes on water consumption, WUE, soil total nitrogen, CEC and total N uptake of rice

Main effects	Water consumption /mm	WUE /kg·m^{-3}	Soil total nitrogen /g·kg^{-1}	CEC /cmol·kg^{-1}	Total N uptake /kg·hm^{-2}
Zeolite levels					
Z_0	822.00a	1.24b	0.71b	15.80Bb	68.31b
Z_1	801.10a	1.35a	0.80a	17.35Aa	92.57a
Water regimes					
W_0	936.86Aa	1.18Bb	0.81a	16.71a	86.04a
W_1	798.65Bb	1.37Aa	0.73a	16.17a	78.78a
W_2	699.15Cc	1.34Aa	0.73a	16.84a	76.51a

Notes: In a column within the same factor, means followed by the same lowercase or capital letter are not significantly different at the 5% and 1% probability levels by Tukey's HSD tests, respectively. WUE and CEC represent water use efficiency and cation exchange capacity, respectively.

3.5 Water consumption and water use efficiency

There were significant interaction effects between Z and W on water consumption and WUE (Table 7). Zeolite application had a significant effect on WUE at the 5% probability level. WUE was also affected by water regimes as well as the water consumption.

Water consumption was numerically less under Z_1 treatment than Z_0 treatment, but the differences were insignificant (Table 8). Compared with W_0 treatment, water consumption under W_1 and W_2 treatment was reduced by 14.8% and 25.4%, respectively. W_2 treatment required 12.5% less irrigation water than W_1 treatment. Figure 3 indicated that water consumption was the lowest under Z_0W_2 treatment, and the highest under Z_0W_0 treatment. Zeolite addition under W_1 treatment required lower water use than Z_0 under the same irrigation. Under both W_0 and W_2 treatments, water consumption did not show significant differences between Z_0 and Z_1 treatment. WUE was the highest under Z_1W_1 treatment, and the lowest under Z_0W_0 treatment (Figure 4). In the Z_0W_0 treatment, although grain yield was high, water consumption was the highest among all the treatments, hence obtaining the lowest WUE. Zeolite addition under W_0 and W_1 treatments both resulted in enhanced WUE compared to non-zeolite control, while zeolite did not show any difference in WUE under W_2 at the $p<0.05$ significant level.

3.6 Correlation studies

The correlation coefficient among grain yield, yield components, water consumption, WUE, total N uptake and soil total nitrogen are shown in Table 9. There were significantly positive correlations between grain yield and effective panicles, spikelets per panicle, water consumption, total N uptake and soil total nitrogen. Among these indexes, effective panicles were most significantly positive related to grain yield with correlation coefficient of 0.85. In addition, spikelets per panicle showed significantly positive correlations with total N uptake and soil total nitrogen. Total N uptake showed significantly positive correlation with soil total nitrogen. This indicated that increase of total N uptake was related to the increase of soil total nitrogen induced by addition of zeolite.

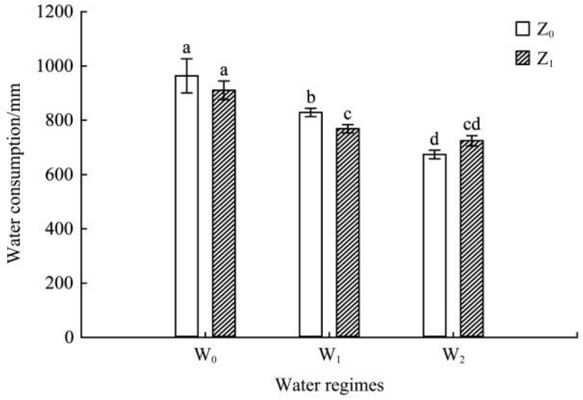


Figure 3 Interaction effects between zeolite application and water regimes on water consumption (2-year mean)

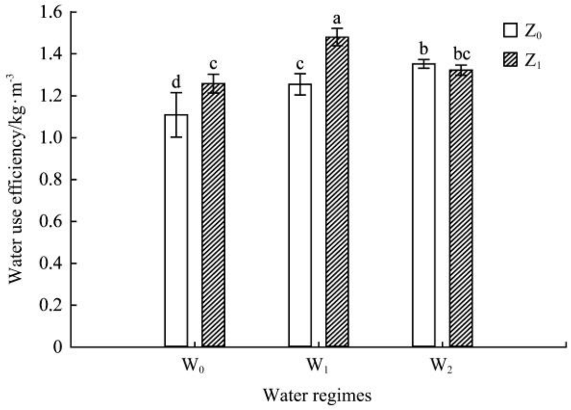


Figure 4 Interaction effects between zeolite application and water regimes on water use efficiency (2- year mean)

Table 9 Correlation analysis among grain yield, yield components, water consumption, water use efficiency, total N uptake and soil total nitrogen

Traits	GY	EP	SP	GFP	TGW	WC	WUE	TNU	STN
GY	1								
EP	0.85^{**}	1							
SP	0.46^{*}	0.05^{ns}	1						
GFP	-0.56^{*}	-0.40^{ns}	-0.45^{ns}	1					
TGW	0.21^{ns}	0.23^{ns}	0.30^{ns}	-0.33^{ns}	1				
WC	0.61^{**}	0.52^{ns}	0.10^{ns}	-0.52^{*}	-0.01^{ns}	1			
WUE	-0.01^{ns}	-0.01^{ns}	0.25^{ns}	0.17^{ns}	0.29^{ns}	-0.76^{**}	1		
TNU	0.60^{**}	0.32^{ns}	0.74^{**}	-0.61^{**}	0.46^{ns}	0.19^{ns}	0.25^{ns}	1	
STN	0.56^{*}	0.35^{ns}	0.71^{**}	-0.55^{*}	0.36^{ns}	0.11^{ns}	0.27^{ns}	0.75^{**}	1

Notes: *, ** and ns denote significance at 5%, and 1% level of probability and non-significance, respectively. GY, EP, SP, GFP, TGW, WC, WUE, TNU and STN represent grain yield, effective panicles, spikelets per panicle, grain filling percentage, 1000-grain weight, water consumption, water use efficiency, total N uptake and soil total nitrogen, respectively.

4 Discussion

4.1 Effects of zeolite application and water regimes on grain yield

Due to the high selectivity of zeolite for large cations, especially for NH_4^+, it has been widely used in crop production to improve nitrogen use efficiency and increase grain yield. By applying zeolite as a soil conditioner, the yield of carrots, eggplant, apples, and wheat were significantly increased by 63%, 19%-55%, 13%-38% and 13%-15%, respectively, only by adding 4-8 t of zeolite per acre[35]. Kavoosi[24] reported that mixture of zeolite at a rate of 8 t/hm^2 and N as urea at a rate of 60 kg/hm^2 in a light-textured soil significantly increased rice grain yield. Sepaskhah and Barzegar[23] also showed that N application rate of 80 kg/hm^2 and zeolite application rate of 4 t/hm^2 could obtain the highest grain yield. Wu et al.[36] reported that zeolite application rate of 10 t/hm^2 mixed with N application rate of 157.5 kg/hm^2 significantly improved rice grain yield compared with conventional nitrogen management. In the present study, Z_1 with zeolite application rate of 15 t/hm^2 significantly increased grain yield by 7.5% compared with Z_0 without addition of zeolite. Z_1 treatment also significantly increased effective panicles, spikelets per panicle and 1000-grain weight compared with Z_0. These traits were yield components and the increment of them contribute to the increase of grain yield. Majid et al.[37], Gül et al.[38] and Polat et al.[39] reported similar results about positive effects of zeolite on yield and yield components of crop. The increase of grain yield could be attributed to reduced nitrogen leaching and increased water holding capacity in soil in the presence of zeolite which improved the nitrogen and water availability for rice growth.

In order to save irrigation water and maintain rice yield simultaneously, lots of water-saving methods have been put forward. Among most of the methods, AWD has been most widely used in rice production. However, the effect of AWD on grain yield still remains debatable, the different results might be attributed to many reasons, such as frequency and duration of water stress, soil hydrological conditions and N fertilizer management[40]. In the present study, W_2 treatment reduced grain yield by 15.3% compared with W_0, while W_1 treatment obtained the comparable grain yield with W_0. This indicated that W_1 treatment could not only save irrigation water, but also maintain rice grain yield compared with continuous flooding irrigation which is similar to the results of Chi et al.[15] Due to the variable sensitivity of rice to soil drying at different growth stages[8], the thresholds for irrigation should be adapted to a specific growth stage. Under W_1 treatment, the thresholds for irrigation are varied with the sensitivity of rice to water stress in different growth stage. For example, under W_1 treatment, rice was not so sensitive to water stress in late tillering stage, the thresholds for irrigation set between –25 kPa to –35 kPa could kill unproductive tillers which could decrease nutrient and water requirement in formation of unproductive tillers, therefore more nutrient and water could be absorbed by productive tillers. In heading-flowering stage, rice was sensitive to water stress which could lead to the risk of spikelet sterility[41], the thresholds for irrigation was set between –5 kPa to –10 kPa in which the water stress was not so severe as –15 kPa under W_2 treatment, so the grain-filling process would not be severely affected. As a result, rice grain yield under W_1 treatment could be improved as compared to W_2. Hence, W_1 treatment could be recommended as an efficient water management to save irrigation water and maintain high grain yield in the rice production of this area.

4.2 Effects of zeolite application and water regimes on water use efficiency

WUE is defined as the ratio of grain yield to water consumption. Due to a high porosity of the crystalline structure of zeolite, it may hold water up to 60% of their weight[39]. Zeolite could save water by increasing the water holding capacity of soil and its availability to plants[25]. Soil water availability is one of the most important factors that influence plant growth and crop yield[42]. Al-Busaidi et al.[43] applied zeolite at a rate of 5 kg/m^2 to sand, finding that soil water content was increased about 2.5% to 4.8% compared with control. Sepaskhah and Barzegar[23] reported that zeolite application rates of 8 t/hm^2 and N application rate of 80 kg/hm^2 could obtain the highest WUE. Abdi et al.[29] indicated that application of zeolite at 3 g/kg to soil increased WUE as compared to unamended treatment. In the present study, WUE under Z_1 treatment was increased by 8.9% in comparison to Z_0. This might be due to the fact that on one hand zeolite could improve total N uptake and increase grain yield, on the other hand it could increase soil water retention and decrease water consumption. Hence, under zeolite addition, the increase of grain yield and decrease of water consumption lead to the improved WUE.

It is urgently necessary to improve WUE in crop production and promote sustainable utilization of water resources[44]. A large number of studies about AWD compared with continuous flooding irrigation had been conducted in many Asia countries such as China, India and the Philippines[9,45,46], indicating that AWD indeed had high water-saving potential. Yao et al.[9] reported that AWD saved 24% and 38% irrigation water in 2009 and 2010, respectively. Belder et al.[40] found that AWD reduced water input by 15%-30% in comparison to CF. Similar results were observed in the present study, compared with W_0 treatment, W_1 and W_2 decreased irrigation water by 14.8% and 25.4%, respectively. Though considerable water-saving potential and WUE, W_2 resulted in a significant decline in yield. However, the use of W_1 not only achieved a comparable water-saving like W_2, but also maintained an acceptable yield performance like W_0, and attained the highest WUE among the three irrigations. There were significant interaction effects between Z and W on WUE. Figure 4 shows that under W_0 or W_1 treatment, Z_1 significantly improved WUE as compared to Z_0. While in the case of W_2 treatment, WUE under Z_1 was not significantly different from that under Z_0. Figure 3 shows that water consumption under Z_1W_2 was less than under Z_1W_1. However, WUE under Z_1W_2 was significantly lower than under Z_1W_1. It may be due to the addition of zeolite resulted in more yield increase under W_1 than under W_2. It also indicated that zeolite application could better alleviate the adverse effect of water stress on rice growth and increase grain yield under W_1 treatment. Therefore, compared with Z_0W_0 (the conventional water management) treatment, Z_1W_1 treatment could be considered as a water-efficient management to obtain a higher WUE in rice production.

4.3 Effects of zeolite application on N uptake of rice

As the most widely used fertilizer in the world, nitrogen is an important limiting factor for crop growth. Increasing nitrogen fertilizer application rate has been a major method to improve crop yield. Farmers try to use excessive nitrogen fertilizer to obtain higher crop yield. Large amounts of N inputs have resulted in low N use efficiency which consequently caused serious environment risk, such as eutrophication, groundwater pollution, and emission of ammonia and greenhouse gases[47,48]. Zeolite have been reported as soil amendment to decrease N leaching, increase N use efficiency and minimize environmental pollution[49].

There are lots of studies in literature indicating the increased N uptake in plant when urea is utilized together with zeolite. Ahmed et al.[50] reported that application of inorganic fertilizers mixed with zeolite significantly improved N uptake in maize tissue compared with treatment without zeolite addition. Majid et al.[37] reported that application of zeolite at a rate of 9 t/hm^2 significantly decreased nitrate leaching compared with control. Gül et al.[38] indicated that application of zeolite resulted in increased plant growth and higher N and K contents in plant tissues. Kavoosi[24] indicated that mixture of zeolite at a rate of 8 t/hm^2 or 16 t/hm^2 and N as urea at a rate of 60 kg/hm^2 obtained higher N uptake by grain and straw than control. In the present study, Z_1 with zeolite application rate of 15 t/hm^2 and traditional N fertilizer application rates obtained a 35.5% higher total N uptake than Z_0 without zeolite addition. This resulted from the unique character of zeolite that influenced soil CEC and in turn increased the NH_4^+ absorption and decreased N loss induced by leaching. There were no significant interaction effects between water regimes and zeolite application on total N uptake. Hence, Z_1W_1 treatment could be recommended to obtain a higher total N uptake and achieve a higher grain yield.

5 Conclusions

In the present study, it is concluded that zeolite application significantly increased grain yield, WUE and total N uptake, and negligibly reduced water consumption. W_1 treatment obtained comparable grain yield with W_0, while W_2 treatment significantly reduced grain yield as compared to W_0. Both W_1 and W_2 treatment remarkably decreased water consumption and improved WUE and W_1 treatment achieved the highest WUE. No significant effect of water regimes on total N uptake was observed. There were significant interaction effects between zeolite application and water regimes on water consumption and WUE. Z_1W_1 treatment obtained the highest WUE. The combined Z_1 and W_1 treatment enhanced spike and root dry weight, effective panicles, spikelets per panicle, and 1000-grain weight, all of which contributed to increased grain yield, and consequently improved WUE and total N uptake with the decreased water consumption by W_1 treatment and enhanced N retention by zeolite addition. Therefore, the results implied that the combined Z_1 (zeolite application of 15 t/hm^2) and W_1 (energy-controlled irrigation) treatment could be recommended to increase rice grain yield, reduce irrigation water and improve WUE on a clay loam soil.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (51679142, 51709173), and the Special Fund for Agro-scientific Research in the Public Interest from the Ministry of Agriculture, China (201303125).

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