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Increasing nitrogen use efficiency with lower nitrogen application frequencies using zeolite in rice paddy fields**

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A b s t r a c t. Zeolite can effectively regulate the nutrient status in the root zone of crops, thereby increasing nitrogen utilization. However, there has been relatively little research conducted concerning a possible reduction in the frequency of nitrogen application due to the sustained-release properties of zeolite. In this study, 157.5 kg ha^{-1} nitrogen in the form of urea fertilizer was applied at the same rate, either as a one-time application or as a 3-way split application with and without 10 t ha^{-1} zeolite. The effects on rice yield, nitrogen uptake, root morphology and soil properties were evaluated in 2014 and 2015. Results showed that zeolite could enhance the biomass, leaf area index and nitrogen uptake. A higher rice grain yield and nitrogen uptake following soil treatment with zeolite could be attributed to a higher soil cation exchange capacity as well as nitrogen and potassium availability in the soil especially during the vegetative period of the rice plant. The addition of nitrogen to the soil as a one-time application or 3-way split application with 10 t ha^{-1} zeolite significantly increased rice grain yield by 8.5 or 10.7% compared with nitrogen as a one-time application without zeolite. Zeolite addition greatly improved the development of root morphology and activity compared with treatments without zeolite, which contributed to additional plant growth. The addition of nitrogen to the soil with 10 t ha^{-1} zeolite as a one-time application that can significantly increase nutrient retention is recommended to improve rice grain yield and decrease nitrogen application frequencies in order to lower both labour forces and energy requirements.

K e y w o r d s: available nitrogen, nitrogen uptake, root system, labour force

INTRODUCTION

Rice has become the most important food crop in Asia because it constitutes approximately 32% of food calorie intake (Belder *et al.*, 2004). Rice is also a daily source of nutrition for 60% of the population of China, the people of that country will require 0.64-0.72 billion t of rice when the population reaches 1.6 billion, and this is expected to occur in 2030 (Liu and Zhang, 2005; Bi *et al.*, 2009). Reductions in fertilizer use may threaten the production of rice. Therefore, novel or at the very least, reasonable nitrogen (N) management strategies must be explored in order to enhance N use efficiency (NUE) and rice productivity.

In paddy soil, N is the most important and widely used fertilizer nutrient, it plays an essential part in developing yield capacity and maintaining photosynthetic activity during the grain filling stage (Wienhold *et al.*, 1995). Hence, management strategies for N are critical for enhancing NUE and rice grain yield (Sandhu *et al.*, 2012). Ideally, N management strategies should apply optimum rates and frequencies, which match crop demand (Belder *et al.*, 2004). Appropriate nitrogen management, where the right amounts of nitrogen are applied and best practices are implemented to ensure higher efficiency use, may enhance the availability of soil N and maintain strong root activity in order to allow the rice plants to increase nitrogen accumulation. However, the improper use of N has resulted in environmental concerns, especially in developing countries (Barea, 2015). NO_3-N present in the soil may be susceptible to leaching and hence contaminate the surface soil and groundwater (Ippolito *et al.*, 2011). At a range of 0.2 to 0.5 mg L^{-1} NH_4-N concentrations could be fatal to fish and aquatic animals (Weatherley and Miladinovic, 2004). Therefore, a reasonable fertilization regime would not only benefit rice growth, but also greatly reduce the ecological load on farmland.

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Zeolites (Z) are crystalline, hydrated aluminosilicates that have three-dimensional crystal structures (Rehakova *et al.*, 2004; Gholamhoseini *et al.*, 2013). As a non-metallic mineral resource, Z has been investigated for the purpose of decreasing N leaching and enhancing soil fertility due to its considerable cation exchange capacity (CEC) and ion adsorbing capacity (Sepaskhah and Yousefi, 2007). NH_4-N in the pores of Z crystals could be released slowly for continuous uptake by plants and also decrease nitrification (Sepaskhah and Barzegar, 2010). Researchers have determined the effects of combining chemical fertilizers with Z and found that Z addition to soil could significantly decrease phosphorus (P) and nitrate leaching (Gholamhoseini *et al.*, 2012). Mixing N with Z significantly increased the rice grain yield due to enhanced N retention in surface soil (Sepaskhah and Barzegar, 2010; Kavoosi, 2007). However, there was a lack of information available concerning research into decreasing N application frequencies using the Z amendment while maintaining higher rice grain yield and N use efficiency.

Therefore, the objectives of the experiment were to investigate the effects of different N application frequencies with Z on rice grain yield, root morphology, CEC, N uptake, available N and K during two growth seasons of 2014 and 2015 in the northeast coastal region of China. Z was only applied in 2014 and no additional Z was applied in 2015.

MATERIALS AND METHODS

The experiment was conducted from May 2014 to October 2015 at Donggang experimental irrigation station (39°52′48″ N latitude, 123°34′48″ E longitude and altitudes of 8.1 m above mean sea level). The area belongs to the continental moist monsoon climatic region of the temperate zone. It is affected by the Yellow Sea and is characterized by a maritime climate. Its average annual air temperature is 8.4°C. The yearly average precipitation which is mainly concentrated in the summer months is 967 mm. The physical and chemical properties of the soil used in the two-year experiment are shown in Table 1 with reference to our previous research (Chen *et al.*, 2014; Wu *et al.*, 2016a). According to Table 1, the soil texture was a silty clay loam.

The field experiment had a completely random design with 3 replications. There were 4 treatments in this experiment: urea was used as basal fertilization once (N_1Z_0); urea was used as basal fertilization once with Z (N_1Z_{10}); urea was used as third-split fertilization according to the traditional fertilization method below (N_3Z_0); urea was used as third-split fertilization with Z (N_3Z_{10}). Z application rates of 10 t ha^{-1} could significantly increase rice grain yield in this region under traditional N regimes (Chen *et al.*, 2014; Wu *et al.*, 2016a). Therefore, Z was applied at an application rate of 10 t ha^{-1} (Z_{10}) for all 4 treatments.

Table 1. Physical and chemical properties of experimental soil

Soil properties	Content
Sand (%)	11.4
Silt (%)	66.7
Clay (%)	21.9
pH	6.61
Bulk density (g cm^{-3})	1.412
Available P (mg kg^{-1})	32.33
Available K (mg kg^{-1})	56.56
Alkali-hydrolysable N (mg kg^{-1})	36.55
Total N (g kg^{-1})	0.677
Organic matter (g kg^{-1})	9.02

The natural Z used in this study originated from Liaoning province, China. Z had the following chemical composition (in %): SiO_2 = 65.56, Al_2O_3 = 10.62, Na_2O = 0.39, K_2O = 2.87, CaO = 2.59, Fe_2O_3 = 0.63, MgO = 0.82, FeO = 0.09, TiO_2 = 0.069, P_2O_5 = 0.001, MnO = 0.01, H_2O = 8.16, and loss of ignition (LOI) = 16.59. Z was applied to the near-surface soil as basal fertilizer with N. Based on the traditional fertilization method in the experimental station, N (157.5 kg ha^{-1}) as urea was applied to the near-surface soil layer in three parts: 60% – basal, 30% – 10 days after transplanting and 10% – 15 days after the jointing-booting stage, respectively. K (K_2O, 72 kg ha^{-1}) was applied in the form of potassium sulfate in two fractions: 50% basal and 50% 15 days after the jointing-booting stage, respectively for all 4 treatments. P (P_2O_5, 172 kg ha^{-1}) was applied as the basal fertilizer. The traditional variety used in the experimental station was Gangyu6 (Japonica rice) for both experiments over two years. Sowing begins on the 22nd of April, with transplanting being conducted on the 28th of May. The seeding recovery stage (R) begins on the 29th of May, the tillering stage (T) on the 5th of June, the jointing-booting stage (J) occurs on 4-6th of July, the heading-flowering stage (H) on 3rd-7th of August, the milky ripening stage (M) on 23rd-28th of August, the yellow ripening stage (Y) on 5-10th of September and rice harvest on 16-20th of September, respectively. Each hill had 3 rice seedlings (7×17-hills per plot). Plot sizes were 2.5×2 m^2 and rice was transplanted at 14×30 cm spacing. The plots were regularly hand-weeded and pesticides were used to prevent insect and pest damage. No noticeable crop damage was observed during the experiment. The water layer in these plots was maintained at 1-7 cm in rice whole growth stages. Water was distributed by pipe to each plot for irrigation. Water depth was measured at a permanently fixed depth gauge. The irrigation water flow was stopped 15 days before harvest.

Crop samples for biomass, N accumulation and leaf area index (LAI) were taken 4-5 times from transplanting onward. The sampling days were on June the 6th and 22nd at the tilling stage, July the 5th and 12th at the jointing-booting stage, August the 6th and 8th at the heading-flowering stage, August the 26th and September the 2nd at the milky ripening stage and September the 15th and 18th at the yellow ripening stage, respectively. At each sampling, 2 hills per plot with 3 replications were removed, separated and rinsed. The dry weight of the plant was determined after drying at 75°C until a constant weight was reached. LAI was determined using a Plant Canopy Analyser LICOR, model-2000. The root cap ratio refers to the ratio of the dry weight of the underground part of the plant to the aboveground part. For each plot, a 0.14 (width)×0.3 (length)×0.3 (active rooting depth) metre clod sample transferred into a mesh bag made from 100 mesh nylon mesh. After water panning, the roots were separated and the root morphology was determined. The roots were randomly selected at the milky-ripening stage to calculate the average main root length and root diameter using Vernier Calipers. The displacement method was used to accurately obtain the volume of the roots. The bleeding rate defined as the root activity was measured using cotton traps (Zhang *et al.*, 2013). After the removal of the rice stem at around 10cm above ground level, pre-weighted absorbent cotton was placed on the cut surface of the stump and wrapped in plastic film secured by a rubber band. Pre-weighed cotton was weighed again after 14 h from 6:00 p.m. till the next day 8:00 a.m. to calculate the bleeding rate.

At the end of the growth stage, the rice grain yield was calculated based on a 12-14% moisture content. The number of panicles was counted from three randomly selected plants and the weight of the grains per panicle was obtained using electronic scales. The unfilled grain percentage and 1000-grain weight were determined after the process of drying and enzyme deactivation.

Soil samples from depths of 0-30 cm (15 cm) were taken both in the vegetative period (15 days after transplanting) and reproductive period (5 days after the milky ripening stage). The soil samples remaining in the centrifuge tubes were extracted using 60 ml of 1M NH_4OAc solution (pH 7.0) followed by steam distillation to determine the soil CEC (Rabai *et al.*, 2013). The total N concentration in the plant and soil were determined by the semi-micro Kjeldahl method and available K was tested using a flame photometer for K available on the exchange sites of Z (Shi and Bao, 1996). Soil samples were passed through a 2 mm sieve after being blended, and air-dried in a laboratory and 5 g of each soil sample was extracted using 50 ml of 2M KCl solution. Concentrations of NH_4-N and NO_3-N were determined using the AA3 Continuous Flow Analytical System (Shi and Bao, 1996; Malekian *et al.*, 2011).

All data (two-year mean) were subjected to analysis of variance (ANOVA) using SAS9.3 software. The separation of the means was performed using least significant difference (LSD).

RESULTS

Figures 1 and 2 show the different growth and development of rice within 4 treatments. Rice plots treated with N_1Z_{10}, N_3Z_0 and N_3Z_{10} produced higher LAI and biomass compared with N_1Z_0. The LAI and biomass of N_1Z_{10} does not seem to differ significantly from those of N_3Z_0. In the rice reproductive period, N_3Z_0 and N_3Z_{10} treatments produced better performances with regard to LAI and biomass whereas N_1Z_0 and N_1Z_{10} exerted a more obvious influence at the initiation of the rice growth stage. Maximum LAI (3.67) and biomass (13893.74 kg ha^{-1}) were observed for N_3Z_{10}. N_3Z_{10} and N_1Z_{10} treatments resulted in a 37.3 and 18.8% heavier biomass compared with N_1Z_0. Compared with N_3Z_0, N_3Z_{10} and N_1Z_{10} increased the biomass by 18.7 and 2.8%, respectively.

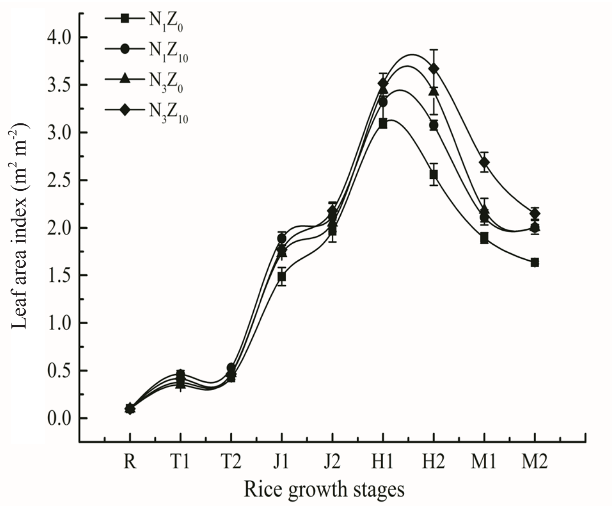

Fig. 1. Leaf area index changes at different rice growth stages. R, T, J, H and M were the stages of recovery stage, tillering stage, jointing-booting stage, heading-flowering stage and milky ripening stage, respectively.

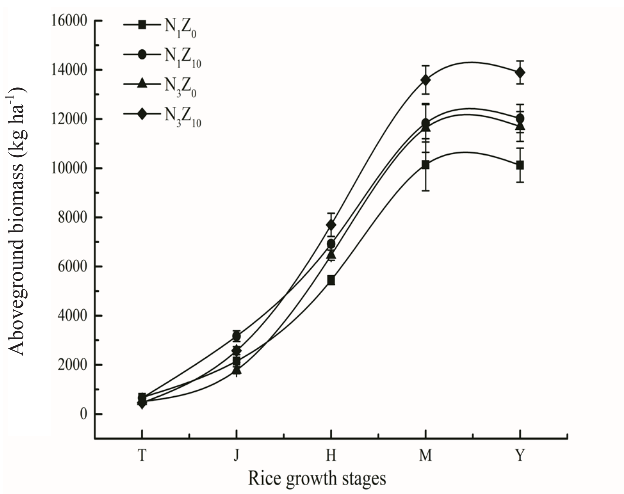

Fig. 2. Biomass changes at different rice growth stages. R, T, J, H, M and Y were the stages of recovery stage, tillering stage, jointing-booting stage, heading-flowering stage, milky ripening stage and yellow ripening stage, respectively.

Table 2. Rice grain yield, yield components, soil residual nitrogen and soil cation exchange capacity as affected by zeolite and nitrogen application at rice harvest time: urea used as basal fertilization one time (N_1Z_0), N_1Z_0 with zeolite (N_1Z_{10}), urea used as third-split fertilization (N_3Z_0), N_3Z_0 with zeolite (N_3Z_{10})

Treatments	Grain yield (t ha^{-1})	1000-grain weight (g)	Unfilled grain percentage (%)	CEC (cmol kg^{-1})	SRN (g kg^{-1})
N_1Z_0	7.28c	26.270c	4.43a	11.99b	0.46a
N_1Z_{10}	7.90ab	26.648b	2.60c	15.01a	0.51a
N_3Z_0	7.74b	26.542b	4.34ab	12.05b	0.47a
N_3Z_{10}	8.06a	26.848a	3.01bc	13.69a	0.49a

Mean values followed by different indices are significant at 0.05 probability level. CEC – soil exchange capacity, SRN – soil residual nitrogen content.

The effects of different combinations of N application frequencies with Z on rice grain yield and yield components are shown in Table 2. Rice grain yield with N_3Z_{10} and N_1Z_{10} treatments were significantly enhanced by 8.5 and 10.7% compared with N_1Z_0. What's more, N_3Z_{10} and N_1Z_{10} treatments can also lead to higher 1000-grain weight and the lower unfilled grain percentage compared with N_1Z_0. It is suggested that the Z amendment could enhance rice grain yield mainly due to the higher 1000-grain weight and lower unfilled grain percentage. However, there is no clear difference between N_1Z_{10} and N_3Z_0 on the 1000-grain weight of rice.

N accumulation at various growth stages of rice in both of the two growing seasons are shown in Fig. 3. Rice with N_3Z_0 and N_3Z_{10} treatments achieved a higher N uptake compared with N_1Z_0 at harvest time, which is in complete contrast to the result from the tilling stage to the jointing-booting stage. This was due to the fact that the applied N was lower than that of N_1Z_0 and N_1Z_{10} treatments at the initial growth stage. The maximum value of N uptake at harvest time (81.61 g kg^{-1}) was observed in N_3Z_{10}. This result suggests that the Z amendment regulated the soil available N from the tillering stage to the jointing-booting stage. The dynamic changes in N matched the N requirement of the rice plant and finally N_3Z_{10} produced a higher grain yield.

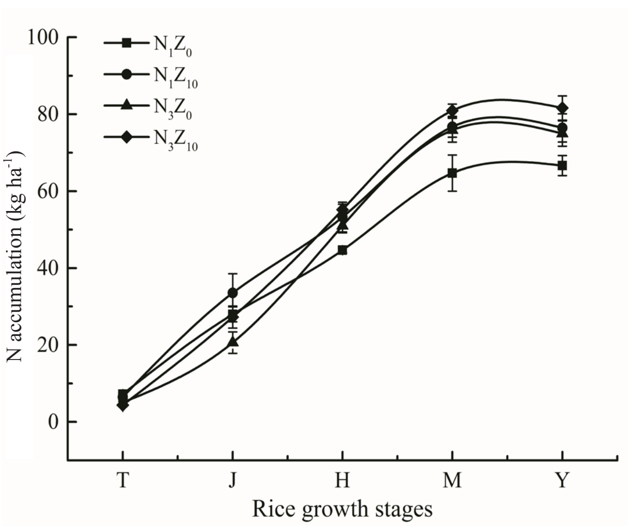

Fig. 3. N accumulation at different rice growth stages. R, T, J, H, M and Y were the stages of recovery stage, tillering stage, jointing-booting stage, heading-flowering stage, milky ripening stage and yellow ripening stage, respectively.

The impacts of different N management regimes on soil residual N (SRN) and CEC are shown in Table 2. Soil water and nutrition supply capacity has been shown to depend on CEC. There were no significant effects on soil CEC between different N application frequencies. Higher soil CEC was achieved at many N application frequencies with Z amendments. However, both N application frequencies and Z had little effect on SRN. The average content of SRN was lower than its original content. This may be due to N losses in the saturated conditions of rice fields. Adequate Z application rates greatly contributed to the CEC and Z amendment that increased soil-available N retention might also exhibit the continuing effect of boosting soil fertility over the next year.

The reasons for the enhancement of dry weight biomass and N accumulation are explored in Table 3. During the vegetative period of rice, N_1Z_0, N_1Z_{10} and N_3Z_{10} treatments achieved higher NH_4-N content in soil compared with N_3Z_0. NO_3-N content of N_1Z_0 treatment resulted in the lowest content of NH_4-N due to long-term N consumption through leaching or uptake by plants under the one-time N application method. It demonstrates that Z addition to soil increased the N availability due to its longer controlled-release time of NH_4-N. However, during the rice reproductive period, there were no clear differences in available N between different treatments, which indicated that the controlled-release function of Z mainly happened at the initial growth stages of rice rather than in the reproductive period.

Regarding the chemical composition, K_2O constitutes a significant portion of Z. In the vegetative period of rice, N_1Z_{10} and N_3Z_{10} treatments considerably increased the available K content of soil compared with N_1Z_0. The K content of N_3Z_0 was higher than that of N_1Z_0 mainly due to the fact that considerable amounts of K were utilized by rice plants under the one-time N application method. During the reproductive period, Z_{10} treatment still significantly

Table 3. NH_4-N, NO_3-N and potassium content in soil as affected by zeolite and nitrogen management in different rice growth periods: urea used as basal fertilization one time (N_1Z_0), N_1Z_0 with zeolite (N_1Z_{10}), urea used as third-split fertilization (N_3Z_0), N_3Z_0 with zeolite (N_3Z_{10})

Treatments	In vegetative period (mg kg^{-1})			In reproductive period (mg kg^{-1})		
	NH_4-N	NO_3-N	K	NH_4-N	NO_3-N	K
N_1Z_0	16.33a	8.49b	274.54c	0.948a	0.841a	25.50c
N_1Z_{10}	17.44a	10.59ab	302.72b	0.952a	0.842a	28.50b
N_3Z_0	11.29b	10.71ab	311.14b	0.986a	0.873a	24.00c
N_3Z_{10}	15.70a	12.81a	353.68a	1.012a	0.863a	30.99a

Mean values followed by different indices are significant at 0.05 probability level.

Table 4. Root system as affected by zeolite and nitrogen managements at the milky-ripening stage: urea used as basal fertilization once (N_1Z_0), N_1Z_0 with zeolite (N_1Z_{10}), urea used as third-split fertilization (N_3Z_0), N_3Z_0 with zeolite (N_3Z_{10}), the root cap ratio refers to the ratio of the dry weight of the underground part to the aboveground part

Treatments	Dry weight (g plant^{-1})	Root cap ratio (%)	Main root length (cm)	Root diameter (mm)	Root volume (cm^3)	Root activity (g h^{-1})
N_1Z_0	6.38c	7.61a	30.81b	0.79b	33.45b	0.11c
N_1Z_{10}	7.56a	9.11a	35.60a	0.98a	38.48a	0.13b
N_3Z_0	6.58bc	8.53a	34.35a	0.91ab	36.15ab	0.13b
N_3Z_{10}	7.16ab	9.59a	37.75a	0.97ab	38.12a	0.15a

Mean values followed by different indices are significant at 0.05 probability level.

increased soil K content compared with Z_0. It appears that the Z amendment increased soil K content throughout the growth period of rice.

Table 4 shows the effects of various N management regimes on rice root morphology and activity. According to Table 4, the Z amendment significantly increased the root dry weight, main root length, diameter, root volume and root activity compared with N_1Z_0. Developed root traits may enhance the nutrient transport from the root to the aboveground parts and result in higher biomass and grain yield. However, Z input did not statistically significantly improve the root cap ratio.

DISCUSSION

N nutrition is one of the most pivotal factors of crop production. The mixture between Z and N, which is comparable to slow-release fertilizers, played an important role in the rice grain yield increasing (Sepaskhah and Barzegar, 2010). Compared with N_1Z_0, the rice grain yield resulting from the N_3Z_{10} and N_1Z_{10} treatments were significantly enhanced by 8.5 and 10.7% mainly due to a higher 1000-grain weight and lower unfilled grain percentage. Similar results were found by Sepaskhah (Sepaskhah and Yousefi, 2007; Sepaskhah and Barzegar, 2010), but they found that the Z amendment could only slightly enhance the 1000-grain weight. However, there were no clear differences between N_1Z_{10} and N_3Z_0 on 1000-grain weight of rice. Some researchers have suggested that the higher 1000-grain weight was obtained mainly due to an enhancement in sink and source parameters (Wu *et al*., 2016a). In the present study, when compared with N_3Z_0, the sink parameter of the N_1Z_{10} treatment was significantly enhanced by the one-time N application.

In our research, N_3Z_{10} and N_1Z_{10} treatments resulted in a 22.4 and 14.7% higher N uptake than N_1Z_0. The difference between N_1Z_{10} and N_3Z_0 was small at harvest time. The dominant reasons for the trend that Z clearly increased N uptake may be (1) NH_4^+ absorption by Z to decrease N losses when N is available at the initial growth stage of rice, and (2) slow release of N in contrast to N management without Z (Gholamhoseini *et al*., 2012; Malekian *et al*., 2011). A larger average content of available N released by Z that corresponded to the N requirement of the rice plant from the jointing-booting stage in surface soil resulted in a higher N uptake. In fact, when N was applied at early days of the plant life cycle, the Z amendment could decrease N availability to the plant due to its high CEC. Ippolito *et al.* (2011) showed that N with a Z amendment contained more NH_4-N at day 7 and less NH_4-N at day 35. It is demonstrated that at the first 7 days, Z decreased N availability to the plant and lead to slow growth. In this experiment, Fig. 3 showed an observable shrinkage in N uptake and biomass at the initial tillering stage with Z addition. However, it is apparent that Z clearly alleviated N stress from the tillering stage to jointing-booting stage. At the jointing-booting stage, N uptake of the N_1Z_{10} and N_3Z_{10} treatments were inclined to be higher than that of N_1Z_0 and N_3Z_0.

N_1Z_{10} and N_3Z_{10} treatments resulted in a higher NH_4-N content in soil compared with N_3Z_0 at the rice tillering stage. However, there were no clear differences in the N available at harvest time, which indicated that the controlled-release function of Z mainly occurred at the initial growth stages of the rice plant rather than in the reproductive period of rice. The slow-release fertilizer allowed for the successive release rate of N to correspond well with the N requirements of crops (Wu *et al.*, 2016b; Geng *et al.*, 2015). Furthermore, the Z amendment could also significantly increase the N availability for crops similarly to the effects of the slow-release fertilizer (Rehakova *et al.*, 2004; Gholamhoseini *et al.*, 2012).

Either in the vegetative period or reproductive period of rice, Z_{10} resulted in a greater average K concentration compared with Z_0. Z improved the N use efficiency through increased N availability and reduced N losses through the leaching of exchange cations, especially Na^+ and K^+ (Leggo, 2000; Harland *et al.*, 1997; Mohammad *et al.*, 2004). Ferguson *et al.* (1986) found that the establishment of creeping bentgrass decreased as the Z application rate increased by 5 to 10% (by volume), this phenomenon was associated with a decrease in Z sodium content. These results suggest that there could be abundant K and slight Na exchanged by NH_4^+ from Z in the surface soil, which might greatly enhance rice growth. Moreover, there may be interaction effects between K and slow-release N to stimulate rice biomass and LAI. Furthermore, a higher total P and available P in the soil with Z treatment may also contribute to higher biomass and LAI to achieve a higher rate of rice production (Gholamhoseini *et al.*, 2012). Natural Z incorporated into soil could improve the long-term soil quality by enhancing soil CEC. This affected the retention of the most essential nutrients for crops such as N, P and K in soil (Li *et al.*, 2013). However, Z also provided some ions such as Ca^{2+} and Mg^{2+} (Doula *et al.*, 2012). The increased content of Ca^{2+} and Mg^{2+} present in the soil with increasing Z application rates may affect soil structure and result in soil hardening. Therefore, appropriate rates of Z are critical for rice farmers to increase rice grain yield.

The NUE is very low with an average of 27.5% in China, which has led to some concerns that excessive N in field negatively may influence the quality of the environment through leaching and volatilization (Malekian *et al.*, 2011; Wu *et al.*, 2016b). Rice roots, as important organs for absorbing water, nutrients, and growth regulation, have a direct influence on aboveground biomass and nutrient use. Root growth can be used to determine the uptake ability of nutrition and water, it also reflects crop growth and development. In our research, it was found that Z input could statistically significantly enhance the root system. There was little information available on the effects of Z on root morphology. However, the effects of slow-release fertilizer on root morphology were known while the effects of N application plus Z are comparable to the slow-release fertilizer of N. Slow-release fertilizer based on biochar can delay root senescence and greatly increase the main root length, volume, active absorption area and root activity, which results in a higher rice grain yield (Zhang *et al.*, 2013). Rice grain yield has a significantly positive correlation with root dry weight, total root length, total root surface area, root bleeding intensity and the root cap ratio. All of these traits could be enhanced by slow-release fertilizer application (Peng *et al.*, 2013). In conclusion, the enhanced N uptake and rice grain yield by Z were not only attributed to higher available N and K content in the soil but they were also attributed to a developed root system.

CONCLUSIONS

The results herein indicated that:

1. Zeolite application could greatly enhance rice growth and development.

2. At the vegetative stage of the life cycle, a higher content of available nitrogen and potassium in soil could contribute to a higher rice grain yield.

3. Using urea as a basal fertilizer in conjunction with zeolite could significantly increase nutrient retention, whilst conserving the biodiversity of the environment of paddy fields, and this approach is recommended in order to improve rice grain yield and decrease fertilizer application frequencies.

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