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Influence of Zeolite and Phosphorus Applications on Water Use, P Uptake and Yield in Rice under Different Irrigation Managements

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Received: 19 July 2019; Accepted: 6 September 2019; Published: 11 September 2019

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Abstract: Phosphorus (P) deficiency often occurs in paddy fields due to its high fixation, and low solubility and mobility in soils, especially under water stress. Available soil P and plant P uptake could be improved through the application of zeolite. However, little is known about the impact of zeolite on P uptake in rice under water stress. A two-year lysimetric experiment using a split-split plot design investigated the effects of zeolite (0 or 15 t ha^{-1}) and P (0 or 60 kg ha^{-1}) applications on water use, P uptake, and grain yield in rice under two irrigation management systems (continuous flooding irrigation (CF) and improved alternate wetting and drying irrigation (IAWD)). Both irrigation systems produced equivalent effective panicles and grain yield. Compared with CF, IAWD reduced water use and aboveground P uptake and improved water-use efficiency (WUE) in rice. The applications of zeolite or P alone increased grain yield, WUE, soil available P, and stem, leaf, and panicle P concentration, and aboveground P uptake, but had no significant effect on water use. The enhanced grain yield induced by zeolite was related to the increase in aboveground P uptake. The zeolite application enhanced NH_4^+–N retention in the topsoil and prevented NO_3^-–N from leaching into deeper soil layers. Moreover, Zeolite made lower rates of P fertilizer possible in paddy fields, with benefits for remaining P supplies and mitigating pollution due to excessive P. These results suggest that the combined application of zeolite and P under improved AWD regime reduced water use, improved P uptake and grain yield in rice, and alleviated environment risk.

Keywords: zeolite; available soil phosphorus; alternate wetting and drying; nitrogen; water use efficiency

1. Introduction

Rice (*Oryza sativa* L.) is a principal grain crop in the world with more than 50 kg of rice consumed per capita per year worldwide [1]. As the largest water consumer in crops, rice uses almost 80% of the freshwater resources allocated to irrigation in Asia [2]. The rapid population growth, increased water requirements for urban and industrial use, and reduced water availability due to contamination and depletion of water resources have seen a decline in freshwater availability [3]. In addition, the less uniform rainfall distribution, both spatially and temporally, caused by climate change leads to reduced water availability [4], which is threatening rice production. The increasing scarcity of freshwater resources is impacting four billion people worldwide [5]. Therefore, the development of water-efficient irrigation practices is essential for reducing water consumption while maintaining or even increasing grain yields to support the increasing world population. Of the available water-efficient management systems, alternate wetting and drying (AWD) irrigation is one of the most commonly used techniques in Asia [3,6].

Phosphorus (P) is an essential macronutrient required for rice production and plays a vital role in rice growth and productivity [7]. The availability of P is often limited due to its high rate of fixation, low solubility, and absence of mobility in soil [8]. In addition, as water and nutrient absorption by plants are closely associated physiological processes [9], P uptake by plants is primarily determined by water availability. With increased soil moisture, P uptake by plants increases mainly due to the higher dissolution of P and enhanced root development [10]. In contrast, the drying condition reduces soil P availability in rice production [11]. Moreover, rice grown in drying soils may need more fertilizer P for optimal grain yields than in flooding conditions, due to the reduced availability of soil P in drying conditions [12]. To meet the requirements of rice for phosphorus, excessive amounts of fertilizer P are often applied to paddy fields, which not only leads to lower P use efficiency but serious environmental risks, such as the eutrophication of surface water resulting from excess P in the surface water [8]. With the limited amount of readily-accessible P reserves in the world, it is crucial to develop an efficient management of fertilizer P to increase P uptake by rice plants for achieving optimal grain yields while reducing the amount of applied P and alleviating environmental pollution, especially under non-continuously-flooded rice systems.

Zeolites are naturally occurring hydrated aluminosilicates of alkaline and alkaline earth elements, which have a three-dimensional rigid crystal structure formed by the SiO_4 and AlO_4 tetrahedra [13]. However, in the structure of the zeolite, Al^{3+} is relatively small and prone to capturing the center position of the tetrahedra, leading to the substitution of Al^{3+} for Si^{4+} that makes the structure negatively charged. The negative charge of zeolite needs to be neutralized by the exchangeable cation, which gives it a high cation exchange capacity (CEC) [14]. Due to their high CEC, zeolites have been extensively used to increase the nutrient use efficiency of fertilizers, such as nitrogen and potassium in agricultural production [15]. Pickering et al. [16] reported that NH_4^+ or K^+-saturated zeolite applied in combination with phosphate rock (PR) increased the solubility of PR and P uptake by plants. The mechanism is that the uptake of NH_4^+ or K^+ by plant vacates exchange sites which are occupied by Ca^{2+}, decreasing the Ca^{2+} concentration in the soil solution and inducing further dissolution of phosphate rock. Other studies have demonstrated that the addition of zeolite to soil increases the fixation ability of P by plants [17,18]. Many studies have reported the effect of zeolite mixed with phosphate rock on P availability in different soils [16,19,20]. In addition, due to its alkaline and negative charges, zeolite could improve soil P availability by mitigating soil pH, reducing soil exchangeable Al and soil acidity, which lead to less P being fixed by metal oxyhydroxides [21]. However, little is known about the response of P availability to zeolite with phosphate fertilizer applied to a paddy field. In addition, the zeolite can increase soil water content due to its higher water holding capacity [22], which could be attributed to its high porosity crystal structure [23]. The application of the zeolite may further increase soil P availability by improving soil moisture. Therefore, it is essential to clarify P uptake by rice in response to zeolite application in a paddy field, especially under water stress.

In this study, we hypothesized that the application of zeolite in combination with phosphorus under alternate wetting and drying paddy field improves grain yield, P uptake, and water use efficiency (WUE) in rice. The objectives of this study were to evaluate the effects of zeolite and phosphorus applications on grain yield, water use, and P uptake in rice under different irrigation regimes.

2. Materials and Methods

2.1. Site Description and Materials

A lysimetric experiment was conducted at the Liaoning Provincial Key Station for Agricultural Irrigation Research, Shenyang, China (42°08′ N, 120°30′ E), during the 2016 and 2017 growing seasons (May–October). The study area has a temperate, continental, monsoon climate with an average annual air temperature of 7.5 °C and a mean annual rainfall of 673 mm. Precipitation and daily mean temperatures during the rice-growing season for both years were recorded using a weather station installed near the site (500 m southeast of the experimental site), and the long-term data (1986–2015) are also presented (Figure 1). The soil in this region is classified as a clay loam at 0–30 cm depth with the main properties as follows: pH 7.4, bulk density 1.50 g cm^{-3}, organic matter 22.30 g kg^{-1}, alkali hydrolysable N 75.41 mg kg^{-1}, Olsen–P 18.39 mg kg^{-1}, exchangeable K 81.28 mg kg^{-1}, total N 0.78 g kg^{-1}, total P 0.48 g kg^{-1}, total K 21.90 g kg^{-1}, and CEC 10.90 cmol kg^{-1}.

Shennong 9765, a local japonica rice (*Oryza sativa*. L) variety, which is characterized by high yield, good quality, and strong disease resistance, was used in this study. Seedlings were sown on 1 May 2016 and 30 April 2017. Transplanting took place on 26 May 2016 and 24 May 2017 with six hills per plot and four seedlings per hill. Fertilization management agreed with local farmers' fertilizer practices. N (210 kg ha^{-1})—urea was applied in three split applications: 43% as a basal dressing, 43% at initial tillering, and 14% at panicle initiation. K (75 kg ha^{-1})—potassium sulfate was applied in two split applications: 50% as basal and 50% at tillering. The zeolite used is a kind of clinoptilolite with particle size ranged from 0.18 to 0.38 mm. The chemical component of zeolite is as following (%): SiO_2 = 65.6, Al_2O_3 = 10.6, Fe_2O_3 = 0.63, FeO = 0.09, MgO = 0.82, CaO = 2.59, H_2O = 8.16, Na_2O = 0.39, K_2O = 2.87, TiO_2 = 0.069, P_2O_5 = 0.001, MnO = 0.010, with a loss on ignition of 16.6. In order to avoid yield loss, weeds were controlled manually, and insects and diseases were controlled by chemicals of chlorpyrifos and tricyclazole, respectively, throughout the whole growth period.

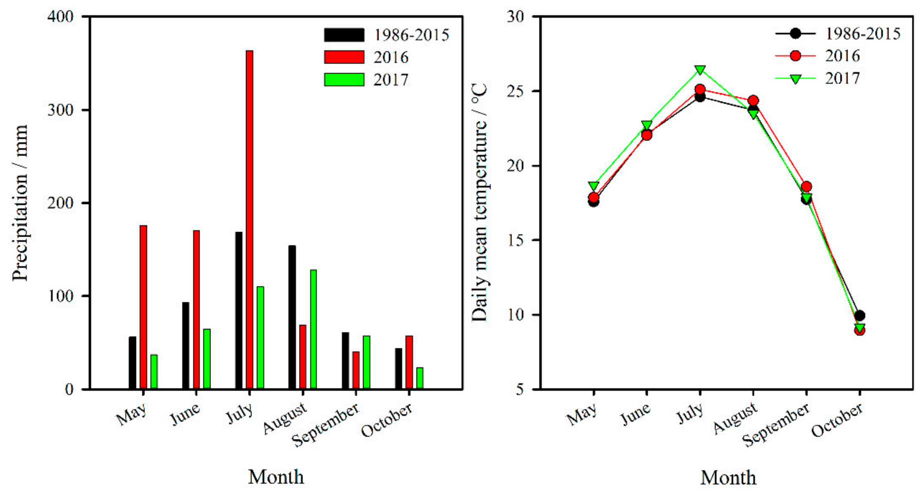

Figure 1. Precipitation and daily mean temperature during the rice-growing seasons in 2016, 2017, and the past 30 years (1986–2015) in Shenyang, Northeast China.

2.2. Experimental Design

The experiment comprised a split-split plot design with three replications. The main plots were two irrigation management systems: continuous flooding (CF) and improved AWD (IAWD) [24]. Within each main plot, subplots were subjected to P applications of 0 or 60 kg ha^{-1} (P_0 and P_{60}, respectively). Sub-sub plots consisted of zeolite applications at 0 or 15 t ha^{-1} (Z_0 and Z_{15}, respectively), based on the recommendation of Chen et al. [25], who confirmed that the zeolite application rate of 15 t ha^{-1} significantly improved rice grain yield in the same study area. Zeolite was only applied in 2016 and mixed into the 0–5 cm layer of soil. The experiment was repeated in 2017 except no addition of zeolite. Each treatment was conducted in a cylindrical weighing lysimeter (0.618 m diameter, 0.80 m high) under a manual rain shelter. The bottom of each lysimeter was filled with a 10 cm layer of coarse gravel. Other parts of the lysimeter were filled with undisturbed soil collected from the field in its original order at 20 cm intervals. There was a drainage valve installed at the bottom of each lysimeter. The experimental design and layout of the plots are shown in Figure 2. From transplanting to the initial tillering stage, a water depth of 10–50 mm was maintained in all treatments to promote seedling establishment. Thereafter, the two irrigation treatments were managed differently. In the CF treatment, the plot was continuously flooded with a water level between 10 and 50 mm until one week before harvest. In the IAWD treatment, the plot was not re-flooded until the soil water potential (SWP)—monitored at 15 cm soil depth using soil water tensiometer installed in the center of each plot—in the middle tillering, late tillering, jointing–booting, heading–flowering, and milky-ripening stages reached −5 to −10 kPa, −25 to −35 kPa, −5 to −10 kPa, −5 to −10 kPa, and −10 to −20 kPa, respectively [24]. Tensiometer readings were recorded daily at 7:00 h, 11:00 h, and 15:00 h. When the readings reached the corresponding thresholds, water was added manually to re-flood the plot to 30 mm above the surface; however, no water layer was kept in the plot in the late tillering stage.

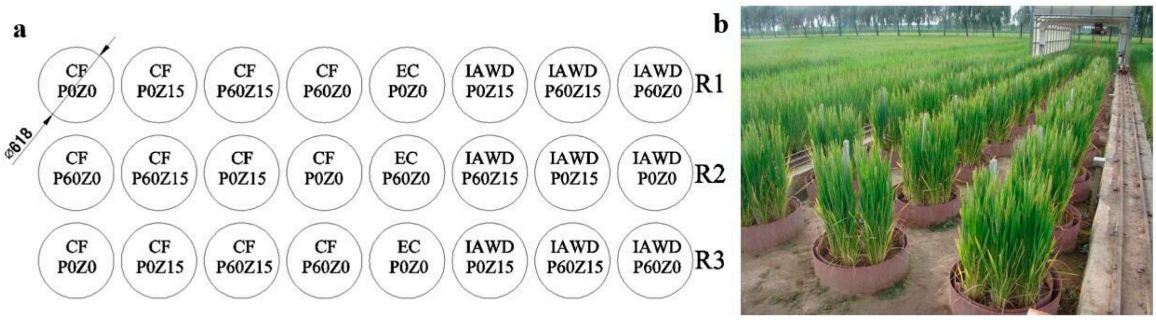

Figure 2. The experimental design (**a**) and layout of plots (**b**) in 2016 and 2017 at the experimental site.

2.3. Sampling and Measurements

Plants were harvested at maturity on 20 September 2016 and 16 September 2017. At harvest, two plants from each plot were randomly collected and separated into three parts: panicles, stems, and leaves. The dry biomass of each part was measured after being oven-dried at 70 °C to constant weight. The samples were then finely ground to pass through a 0.15 mm sieve, which were used for P content determination. Tissue P concentration was determined using the colorimetric method as described by Yoshida et al. [26]. Aboveground P uptake was the sum of the P uptake from the different plant parts, which was computed by multiplying the P concentration and dry weight in each part.

The remaining four hills from each plot were harvested for yield and yield component determination. The plants were air-dried for about five days, and then the grains were hand-threshed to determine the yield based on 14% moisture. Yield components—effective panicles, 1000-grain weight, grain filling percentage, and spikelets per panicle—were measured.

After harvest, soil samples from 0–30 and 30–60 cm depths in each plot were collected. NO_3^-–N and NH_4^+–N concentration in the samples were measured using the methods described by Mulvaney [27]. Available P in the topsoil (0–30 cm) was extracted with 0.5 mol L^{-1} $NaHCO_3$ solution and measured using the procedures described by Murphy and Riley [28].

The lysimeters were weighed with an electrical balance from transplanting to harvest at 10-day intervals. Water consumption for rice in each period was calculated using the following Equation:

$$WC = (G_1 + I - G_2) \times 10^4 / (\rho_0 \times A) \quad (1)$$

where WC is the crop water consumption (m^3 ha^{-1}), G_1 and G_2 are the initial and final weight of the lysimeter in each period, respectively (kg), I is the amount of irrigation water during this period (kg),

ρ_0 is the water density (kg m^{-3}), and A is the plot area (m^2). Total water consumption (TWC) is the sum of water consumption in each period (m^3 ha^{-1}). Water use efficiency was calculated as follows:

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{TWC} \tag{2}$$

where WUE is the water use efficiency (kg m^{-3}) and Y is the grain yield (kg ha^{-1}).

2.4. Statistical Analysis

Data were analyzed as a split-split-split plot design using the GLM procedure for analysis of variance via the statistical analysis system (SAS) software [29], considering years, irrigation regime, phosphorus application, and zeolite application as fixed effects, and replications as random effects. Treatment means were compared at the 5% probability level using the Tukey's honestly significant difference (HSD) tests. Regression analysis was performed by R studio (version 1.1.453) to identify the relationship between the grain yield and the aboveground P uptake.

3. Results

3.1. Grain Yield and Yield Components

The analysis of variance indicated that irrigation regime (I) had no significant effect on grain yield or yield components. Phosphorus application (P) had a significant effect on grain yield, effective panicles, and spikelets per panicle, while zeolite application (Z) had a significant effect on grain yield and yield components except for grain filling percentage. Furthermore, a significant P and zeolite interactions occurred for spikelets per panicle, and irrigation, P, and zeolite interactions for grain yield (Table 1).

Table 1. Analysis of variance for the main and interaction effects of years (Y), irrigation regime (I), phosphorus (P), and zeolite (Z) on grain yield, yield components, total water consumption, water use efficiency, aboveground dry weight, shoot P concentration, aboveground P uptake, and soil available P in 2016 and 2017.

Source of Variation	df	GY	EP	SP	GFP	TGW	TWC	WUE	ADW	SPC	LPC	PPC	APU	SAP
Y	1	*	**	*	ns	ns	**	*	ns	**	*	**	**	**
I	2	ns	ns	ns	ns	ns	**	**	**	**	**	**	**	*
Y × I	2	*	*	*	ns	ns	**	*	**	ns	ns	**	**	ns
P	1	**	**	**	ns	ns	ns	**	ns	**	**	*	*	**
Y × P	1	*	ns	**	ns	ns	ns	ns	ns	ns	**	*	ns	ns
I × P	2	ns	ns	ns	ns	ns	ns	ns	ns	**	**	ns	ns	ns
Y × I × P	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	*
Z	1	**	**	**	ns	**	ns	**	**	**	**	*	**	**
Y × Z	1	**	*	ns	ns	ns	ns	**	*	**	*	ns	*	ns
I × Z	2	ns	ns	ns	ns	ns	ns	ns	**	ns	*	ns	ns	ns
P × Z	1	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × I × Z	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y × P × Z	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
I × P × Z	2	*	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
Y × I × P × Z	2	*	ns	ns	ns	ns	*	**	ns	ns	*	ns	ns	ns

GY, grain yield; EP, effective panicles; SP, spikelets per panicle; GFP, grain filling percentage; TGW, 1000-grain weight; TWC, total water consumption; WUE, water use efficiency; ADW, aboveground dry weight; SPC, stem P content; LPC, leaf P content; PPC, panicle P content; APU, aboveground P uptake; SAP, soil available P. ** and * denotes significance at the 0.01 and 0.05 probability levels, respectively. ns denote non-significance.

The $I_{CF}P_{60}Z_{15}$ (continuous flooding with phosphorus rate of 60 kg ha^{-1} and zeolite rate of 15 t ha^{-1}) and $I_{IAWD}P_{60}Z_{15}$ treatments produced the highest grain yields in both years, being 12.0% and 8.9%, and 8.6% and 7.7% higher than the conventional management practice ($I_{CF}P_{60}Z_0$) in 2016 and 2017, respectively (Table 2). Regardless of the irrigation regime and zeolite application, the P application increased the grain yield by 17.2% in 2016 and 13.2% in 2017, relative to the non-phosphorus treatment. Averaged across irrigation regime and phosphorus, the zeolite application increased grain yield by 12.0% in 2016 and 7.8% in 2017, relative to the no-zeolite control. In line with grain yield, 2017 produced more effective panicles than 2016. Zeolite application (15 t ha^{-1}) produced more effective panicles than the no-zeolite treatment, as did P application (Table 2). Zeolite and phosphorus applications increased spikelets per panicle in both years. Moreover, the increased spikelets per panicle induced by zeolite were greater at P_0 than P_{60} except for the CF treatment in 2016. The irrigation, phosphorus, and zeolite treatments had no significant effect on grain filling percentage in either year. Zeolite application increased 1000-grain weight, relative to the no-zeolite treatment (Table 2).

Table 2. Grain yield and yield components of rice affected by irrigation regime, and phosphorus and zeolite applications in 2016 and 2017.

Year	Irrigation Regime	Phosphorus Application	Zeolite Application	Grain Yield (t ha^{-1})	Effective Panicles	Spikelets Per Panicle	Grain Filling Percentage (%)	1000-Grain Weight (g)
2016	CF	P_0	Z_0	9.44c	14.0bcd	129.6e	97.1a	24.7a
			Z_{15}	10.40b	14.8ab	136.1de	96.5a	24.9a
		P_{60}	Z_0	10.81b	14.5abc	147.3bc	97.0a	24.3a
			Z_{15}	12.11a	15.2a	153.0ab	96.9a	25.4a
	IAWD	P_0	Z_0	8.72d	13.2d	130.9e	97.0a	24.3a
			Z_{15}	10.29b	13.8cd	141.7cd	97.1a	24.9a
		P_{60}	Z_0	10.84b	14.2bc	152.7ab	96.9a	24.9a
			Z_{15}	11.77a	14.7abc	159.5a	96.8a	25.0a
2017	CF	P_0	Z_0	10.16d	14.2c	140.7d	97.0a	24.9a
			Z_{15}	11.05c	16.0ab	155.0bc	97.1a	25.5a
		P_{60}	Z_0	11.60b	15.3abc	158.8abc	97.6a	25.1a
			Z_{15}	12.60a	16.7a	163.6a	97.2a	25.5a
	IAWD	P_0	Z_0	10.41d	14.7bc	141.5d	97.4a	24.6a
			Z_{15}	11.07c	15.5abc	153.2c	97.4a	24.9a
		P_{60}	Z_0	11.64b	15.7abc	154.5bc	97.5a	24.4a
			Z_{15}	12.49a	16.7a	162.1ab	97.3a	25.0a

Within a column for each year, means followed by different letters are significantly different at $P < 0.05$ by Tukey's honestly significant difference test. CF and IAWD are continuous flooding and improved alternate wetting and drying irrigation, respectively. P_0 and P_{60} are phosphorus application rates of 0 and 60 kg ha^{-1}, respectively. Z_0 and Z_{15} are zeolite application rates of 0 and 15 t ha^{-1}, respectively.

3.2. Total Water Consumption and WUE

The effect of irrigation regime (I) was significant for total water consumption (TWC) and WUE (Table 1). The phosphorus (P) and zeolite (Z) effects were significant for WUE. There were significant year and irrigation interactions for total water consumption and WUE, year and zeolite interactions for WUE, and year, irrigation, P, and zeolite interactions for total water consumption and WUE.

Total water consumption in 2017 was higher than in 2016 (Table 3). Regardless of phosphorus and zeolite application, the IAWD treatment reduced the total water consumption by 18.4% in 2016 and 7.9% in 2017, relative to the CF treatment. No significant phosphorus or zeolite effects were observed for total water consumption, though slightly lower total water consumption occurred with the application of zeolite in the $I_{IAWD}P_{60}$ treatment in both years (Table 3).

In general, WUE in 2017 was lower than in 2016 (Table 3). Averaged across phosphorus and zeolite treatments, the IAWD treatment increased WUE by 19.0% in 2016 and 9.2% in 2017, relative to the CF treatment. Regardless of the irrigation and zeolite treatments, P application increased WUE by 12.9% in 2016 and 14.2% in 2017, relative to the no-phosphorus control. Averaged across irrigation and P treatments, the application of zeolite improved WUE by 15.2% in 2016 and 8.0% in 2017, relative to the no-zeolite control. The increased WUE by zeolite or P application was attributed to the enhanced grain yield, as no significant zeolite or P effect was observed on the total water consumption. The highest WUE occurred in the $I_{IAWD}P_{60}Z_{15}$ treatment in both years, being 37.0% and 18.5% higher than the conventional management practice ($I_{CF}P_{60}Z_0$) in 2016 and 2017, respectively.

Table 3. Total water consumption (TWC), water use efficiency (WUE), aboveground dry weight (ADW), and aboveground P uptake (APU) of rice affected by irrigation regime, phosphorus, and zeolite applications in 2016 and 2017.

Year	Irrigation Regime	Phosphorus Application	Zeolite Application	TWC (10^3 m^3 ha^{-1})	WUE (kg m^{-3})	ADW (t ha^{-1})	APU (kg ha^{-1})
2016	CF	P_0	Z_0	7.03a	1.34d	16.4b	27.4b
			Z_{15}	7.03a	1.48cd	19.0a	37.0a
		P_{60}	Z_0	7.40a	1.46cd	18.3a	33.0ab
			Z_{15}	6.78ab	1.79ab	19.1a	37.4a
	IAWD	P_0	Z_0	5.57c	1.57bc	15.5b	26.3b
			Z_{15}	5.57c	1.85a	16.0b	30.6ab
		P_{60}	Z_0	6.02bc	1.80a	15.9b	28.2b
			Z_{15}	5.89c	2.00a	16.4b	29.4b
2017	CF	P_0	Z_0	7.88a	1.29d	16.4c	39.7b
			Z_{15}	7.71ab	1.43cd	19.4ab	56.3ab
		P_{60}	Z_0	7.68ab	1.51bc	17.4abc	53.9ab
			Z_{15}	7.93a	1.59b	19.9a	69.3a
	IAWD	P_0	Z_0	7.17bc	1.45bc	18.1abc	33.0b
			Z_{15}	7.32abc	1.51bc	18.5abc	38.3b
		P_{60}	Z_0	7.28abc	1.60b	16.8bc	32.9b
			Z_{15}	6.98c	1.79a	19.2abc	44.2b

Within a column for each year, means followed by different letters are significantly different at $P < 0.05$ by the Tukey's honestly significant difference test. CF and IAWD are continuous flooding and improved alternate wetting and drying irrigation, respectively. P_0 and P_{60} are phosphorus application rates of 0 and 60 kg ha^{-1}, respectively. Z_0 and Z_{15} are zeolite application rates of 0 and 15 t ha^{-1}, respectively.

3.3. Aboveground Dry Weight and P Uptake

The effect of phosphorus was significant for stem P concentration (SPC), leaf P concentration (LPC), panicle P concentration (PPC), and aboveground P uptake (APU) (Table 1). Irrigation and zeolite had significant effects on aboveground dry weight (ADW), stem P concentration, leaf P concentration, panicle P concentration, and aboveground P uptake. There were significant irrigation and P interactions for stem P concentration and leaf P concentration, irrigation and zeolite interactions for aboveground dry weight and leaf P concentration, and irrigation, P, and zeolite interactions for the aboveground dry weight (Table 1).

The highest aboveground dry weight occurred in the $I_{CF}P_{60}Z_{15}$ treatment in both years (Table 3). The $I_{IAWD}P_{60}Z_{15}$ treatment produced less aboveground dry weight than the $I_{CF}P_{60}Z_{15}$ treatment in 2016 with no significant differences observed in 2017. The IAWD and CF treatments had similar aboveground dry weight in 2017, but the IAWD treatment produced less aboveground dry weight than the CF treatment in 2016. Regardless of irrigation or zeolite treatments, P application increased aboveground dry weight by 4.4% in 2016, relative to the no-phosphorus treatment. Averaged across irrigation and phosphorus treatments, zeolite application increased aboveground dry weight by 6.6% in 2016 and 12.0% in 2017, relative to the no-zeolite control.

In general, stem P concentration in 2017 was higher than in 2016 (Table 4). Averaged across phosphorus and zeolite treatments, stem P concentration declined in the IAWD treatment by 32.0% in 2016 and 32.5% in 2017, relative to the CF treatment. Phosphorus application increased stem P concentration in both years, regardless of irrigation and zeolite treatments. Averaged across irrigation and phosphorus treatments, zeolite application increased stem P concentration by 20.3% in 2016 and 5.1% in 2017, relative to the no-zeolite control. Moreover, the increased stem P concentration induced by P was greater in the CF treatment than the IAWD treatment in both years (Table 4). In line with stem P concentration, leaf P concentration and panicle P concentration were also higher in 2017 than in 2016 (Table 4). Regardless of the phosphorus and zeolite treatments, leaf P concentration declined in the IAWD treatment in both years, relative to the CF treatment. Leaf P concentration increased with the P application in both years. Averaged across irrigation and phosphorus treatments, zeolite application increased leaf P concentration by 32.7% in 2016 and 16.5% in 2017, relative to the no-zeolite treatment. The increase in leaf P concentration induced by phosphorus and zeolite applications was greater in the CF treatment than the IAWD treatment in both years (Table 4). Compared with the CF treatment, panicle P concentration declined in the IAWD treatment in both years. Phosphorus application increased panicle P concentration, relative to the no-phosphorus treatment. Averaged across irrigation and phosphorus treatments, zeolite application increased panicle P concentration by 7.4% in 2016 and 14.1% in 2017, relative to the no-zeolite control.

Table 4. Stem P concentration (SPC), leaf P concentration (LPC), and panicle P concentration (PPC) of rice, and available soil P (SAP) as affected by irrigation regime, phosphorus, and zeolite applications in 2016 and 2017.

Year	Irrigation Regime	Phosphorus Application	Zeolite Application	SPC ($g\ kg^{-1}$)	LPC ($g\ kg^{-1}$)	PPC ($g\ kg^{-1}$)	SAP ($mg\ kg^{-1}$)
2016	CF	P_0	Z_0	0.41bcd	0.29c	2.93a	20.0cd
			Z_{15}	0.47ab	0.37b	3.15a	21.7bc
		P_{60}	Z_0	0.47abc	0.47a	2.88a	21.7bc
			Z_{15}	0.55a	0.53a	3.15a	25.5a
	IAWD	P_0	Z_0	0.29e	0.24c	2.74a	17.9d
			Z_{15}	0.35de	0.36b	3.00a	19.7cd
		P_{60}	Z_0	0.29e	0.25c	2.90a	19.6cd
			Z_{15}	0.37cde	0.38b	3.00a	23.6ab
2017	CF	P_0	Z_0	0.48c	0.47abc	3.94abc	21.4ab
			Z_{15}	0.52b	0.49ab	4.69abc	26.4a
		P_{60}	Z_0	0.52b	0.45bcd	5.13ab	25.4a
			Z_{15}	0.55a	0.55a	5.61a	27.1a
	IAWD	P_0	Z_0	0.33f	0.33ef	3.03c	18.7b
			Z_{15}	0.35ef	0.41cde	3.36bc	23.4ab
		P_{60}	Z_0	0.36de	0.32f	3.20bc	23.1ab
			Z_{15}	0.36d	0.38def	3.78abc	27.2a

Within a column for each year, means followed by different letters are significantly different at $P < 0.05$ by the Tukey's honestly significant difference test. CF and IAWD are continuous flooding and improved alternate wetting and drying irrigation, respectively. P_0 and P_{60} are phosphorus application rates of 0 and 60 kg ha^{-1}, respectively. Z_0 and Z_{15} are zeolite application rates of 0 and 15 t ha^{-1}, respectively.

Aboveground P uptake was significantly higher in 2017 than in 2016 (Table 3). In both years, aboveground P uptake declined in the IAWD treatment, relative to the CF treatment. Aboveground P uptake increased with P application in both years. Regardless of irrigation and phosphorus treatments, zeolite application increased aboveground P uptake by 16.9% in 2016 and 30.5% in 2017, relative to the no-zeolite control (Table 3). Furthermore, grain yield had a significant correlation with the aboveground P uptake, as shown in Figure 3.

3.4. Soil Available P and Inorganic N Content

Irrigation, phosphorus, and zeolite had significant effects on soil available P (SAP) (Table 1). There were significant irrigation and P, and year, irrigation, and P interactions for the available soil P. Regardless of phosphorus and zeolite treatments, available soil P decreased in the IAWD treatment, relative to the CF treatment in both years (Table 4). Phosphorus application increased soil available P compared with the no-phosphorus control in both years. Averaged across irrigation and phosphorus treatments, the application of zeolite increased the available soil P by 14.1% in 2016 and 17.5% in 2017, relative to the no-zeolite treatment.

The 0–30 cm soil depth had significantly higher NH_4^+–N concentrations than 30–60 cm depth in both years (Figure 4). The application of zeolite increased the NH_4^+–N concentrations at 0–30 cm more than at 30–60 cm in both years. Additionally, the CF treatments ($I_{CF}Z_0$ and $I_{CF}Z_{15}$) had higher NH_4^+–N concentrations in soil than the IAWD treatments ($I_{IAWD}Z_0$ and $I_{IAWD}Z_{15}$), regardless of zeolite application, in both years. The $I_{IAWD}Z_{15}$ treatment had higher NH_4^+–N concentrations at 0–30 cm soil depth than the $I_{IAWD}Z_0$ treatment, suggesting that the application of zeolite improves NH_4^+–N retention in soil under alternate wetting and drying irrigation. The soil in the IAWD treatments had higher NO_3^-–N concentrations than that in the CF treatments in both years, regardless of the application of zeolite. The NO_3^-–N concentrations of soil amended with zeolite ($I_{CF}Z_{15}$ and $I_{IAWD}Z_{15}$) differed from those in the unamended soil ($I_{CF}Z_0$ and $I_{IAWD}Z_0$) in both years (Figure 4). The zeolite-amended treatments had significantly lower NO_3^-–N concentrations at 30–60 cm soil depth than at 0–30 cm soil depth. However, the reverse was true for the unamended soil. In both years, the $I_{IAWD}Z_{15}$ treatment had lower NO_3^-–N concentrations at 30–60 cm soil depth than the $I_{IAWD}Z_0$ treatment, suggesting that the application of zeolite reduces NO_3^-–N leaching to deeper soil layers, and therefore, alleviates NO_3^{-}–N contamination of groundwater.

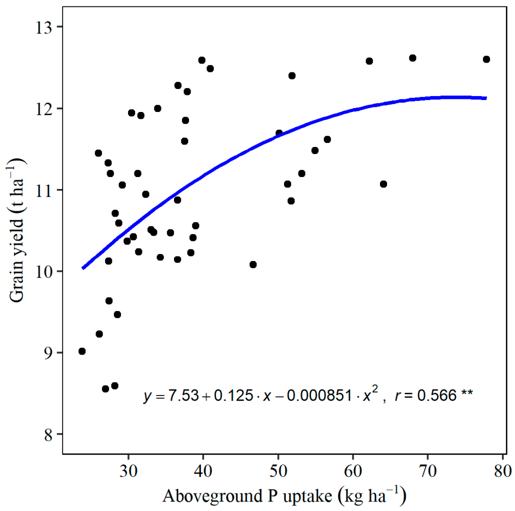

Figure 3. The relationship between grain yield and aboveground P uptake in rice (n = 48). ** denotes significant correlation at $P < 0.01$.

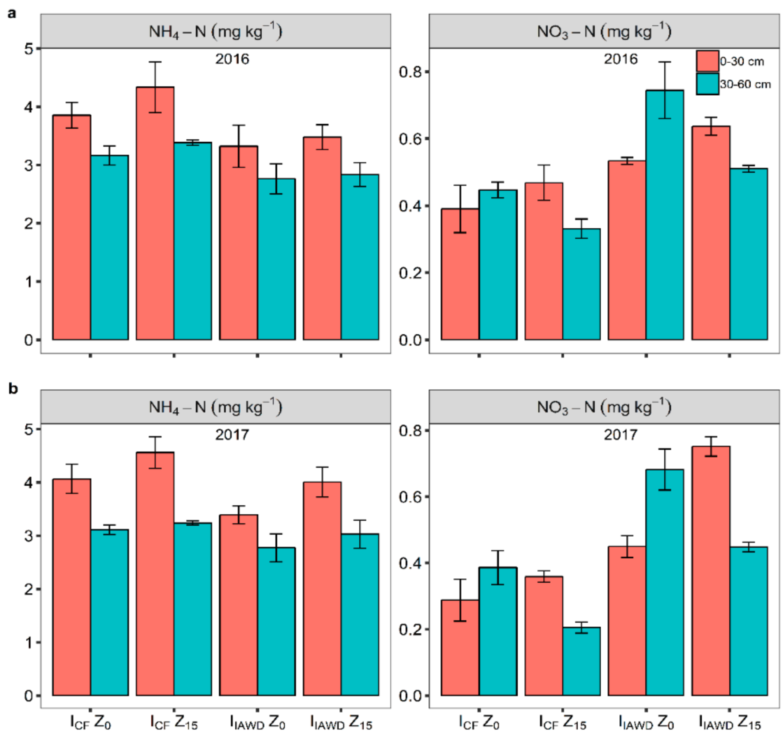

Figure 4. NH_4^+–N and NO_3^-–N concentration in soil at harvest after different irrigation regimes and zeolite applications in 2016 (**a**) and 2017 (**b**).

3.5. Correlation Among Traits

Grain yield was positively correlated with total water consumption (r = 0.32, $P < 0.05$), water use efficiency (r = 0.45, $P < 0.01$ for this and all following traits), stem P content (r = 0.41), leaf P content (r = 0.56), panicle P content (r = 0.47), aboveground dry weight (r = 0.53), aboveground P uptake (r = 0.55), available soil P (r = 0.78), NH_4_30 (r = 0.53), and NO_3_30 (r = 0.35) (Table 5). Among these traits, leaf P content, aboveground dry weight, aboveground P uptake, soil available P, and NH_4_30 had stronger correlations with grain yield (r > 0.50). Stem, leaf, and panicle P contents were positively correlated with available soil P. The aboveground dry weight had significant correlations ($P < 0.01$) with the aboveground P uptake (r = 0.65), available soil P (r = 0.60), and NH_4_30 (r = 0.45). The aboveground P uptake was positively correlated with the available soil P (r = 0.64).

Table 5. Correlation analysis of grain yield, total water consumption, water use efficiency, shoot P concentration, aboveground dry weight, aboveground P uptake, soil available P, NH_4^+–N and NO_3^-–N contents at 0–30 cm soil depth as affected by irrigation regime, phosphorus, and zeolite applications.

Traits	GY	TE	WUE	SPC	LPC	PPC	ADW	APU	SAP	NH_4_30	NO_3_30
GY	1										
TE	0.32 *	1									
WUE	0.45 **	−0.70 **	1								
SPC	0.41 **	0.63 **	−0.28 ^{ns}	1							
LPC	0.56 **	0.60 **	−0.13 ^{ns}	0.84 **	1						
PPC	0.47 **	0.58 **	−0.19 ^{ns}	0.59 **	0.60 **	1					
ADW	0.53 **	0.58 **	−0.17 ^{ns}	0.54 **	0.62 **	0.43 **	1				
APU	0.55 **	0.62 **	−0.18 ^{ns}	0.64 **	0.69 **	0.96 **	0.65 **	1			
SAP	0.78 **	0.49 **	0.13 ^{ns}	0.58 **	0.64 **	0.57 **	0.60 **	0.64 **	1		
NH_4_30	0.53 **	0.33 *	0.07 ^{ns}	0.57 **	0.61 **	0.41 **	0.45 **	0.47 **	0.51 **	1	
NO_3_30	0.35 *	−0.35 *	0.58 **	−0.34 *	−0.08 ^{ns}	−0.21 ^{ns}	0.11 ^{ns}	−0.14 ^{ns}	0.15 ^{ns}	0.07 ^{ns}	1

GY, grain yield; TE, total evapotranspiration; WUE, water use efficiency; SPC, stem P content; LPC, leaf P content; PPC, panicle P content; ADW, aboveground dry weight; APU, aboveground P uptake; SAP, soil available P, NH_4_30 and NO_3_30 represent NH_4^+–N and NO_3^-–N contents at the 0–30 cm soil depth, respectively. * and ** denote significance at 5% and 1% probability level, respectively. ^{ns} denotes no significance.

4. Discussion

4.1. Effect of Irrigation, Phosphorus and Zeolite Application on Grain Yield

The higher grain yields in 2017 relative to 2016 could be attributed to differences in the weather conditions between the years. From heading to flowering (mainly in July), precipitation was significantly lower in 2017 than in 2016, and temperatures were relatively high during this period (Figure 1), which agrees with the findings of Lampayan et al. [30] who found that rice performed better and produced higher grain yields when grown at higher temperatures with more solar radiation. In addition, the higher grain yields in 2017 than 2016 were closely related to the increase in effective panicles (Table 2).

The CF and IAWD regimes produced similar grain yields each year. Yang et al. [31], and Cao et al. [32] reported that moderate AWD maintained or increased rice grain yield, relative to the CF treatment. Bueno et al. [33] reported that AWD with an SWP threshold of −30 kPa did not reduce grain yield. However, Bouman and Tuong [2] reported that higher SWPs up to −30 kPa might reduce yields in some situations. Wiangsamut [34] reported >30% yield reductions in sandy loam, silt loam, and loam soils when the SWP threshold was −30 kPa. The discrepancies reported above may be related to differences, such as soil properties, the severity of soil drying between irrigations, weather conditions throughout the rice-growing season, and cultivar differences [35–37]. Whether AWD-imposed irrigation leads to a yield penalty or not in rice depends on the intensity of the SWP threshold before reflooding, as well as when the drying occurs relative to the stage of growth [30]. In our study, the SWP threshold under the improved AWD (IAWD) treatment varied with growth stage, depending on the sensitivity of the rice plant to water deficit at each stage, which resulted in grain yields that were similar to CF. The results are in line with Yang et al. [38] who indicated that the

SWP threshold of controlled irrigation related to specific growth stages could reduce irrigation water use and improve rice grain yield.

Zeolite, used as a soil amendment, could increase the yield of upland crops [39–41] and lowland rice [25,42]. In our study, zeolite applied into clay loam paddy fields increased grain yield in both years, relative to the unamended control, and was related to the increase in effective panicles, spikelets per panicle, and 1000-grain weight (Table 2). In addition, the grain yield of $I_{IAWD}P_{60}Z_{15}$ treatment is higher than $I_{CF}P_{60}Z_{0}$treatment in both years (Table 2), indicating that zeolite might increase grain yield through maintaining soil available water-holding capacity under IAWD regime. Usually, NH_4^+ derived from urea hydrolysis after application of N fertilizer is nitrified immediately before being absorbed by plants. The large CEC of zeolite means it has a high affinity for plant nutrients, especially NH_4^+. Zeolite added to the field can adsorb the NH_4^+ present in fertilizer, which is gradually desorbed and taken up by plants to inhibit nitrification of NH_4^+ to NO_3^-, which improves plant growth and grain yield [43]. This was confirmed in the present study, where the zeolite-amended topsoil (0–30 cm) had a higher NH_4^+ content than unamended soil in both years (Figure 4). The reduced NO_3^- content in the deeper soil layers (30–60 cm) in the zeolite-amended treatment might be because zeolite reduces nitrate leaching by retaining more NH_4^+ in the topsoil, which could alleviate NO_3^- contamination in groundwater. Additionally, the significant increase in the aboveground P uptake in response to zeolite application may explain the improved grain yield, as grain yield positively correlated with aboveground P uptake (Figure 3). Similar results were reported by Ahmed et al. [15] and Pickering et al. [16], who found that zeolite mixed with phosphorus applied to soil significantly increased P uptake by plants.

Application of phosphorus significantly increased grain yield relative to the no-phosphorus treatment (Table 2). Rice growth and grain yield reportedly increased with phosphorus supply [44,45] and could be attributed to the increase in effective panicles and spikelets per panicle (Table 2). The increased aboveground P uptake with phosphorus application could also explain the increase in grain yield (Figure 3).

4.2. Effect of Irrigation, Phosphorus, and Zeolite Application on Water Use

Mao [46] reported that AWD saved irrigation water by reasonably adjusting water provision during the key growing phases in rice, and corresponded with the physiological water requirement of rice. Numerous studies in Asian countries, such as China [47], India [48], and the Philippines [49] have indicated that AWD has the potential to save more water than CF. Usually, the decrease in irrigation water requirements is attributed to the reduction in percolation and evapotranspiration [50]. Since there was no percolation in the present study, evapotranspiration was equal to the irrigation water requirement. Pan et al. [47] reported that AWD decreased irrigation water use by 24.1% and 74.5% in 2014 and 2015, respectively. Carrijo et al. [51] conducted a meta-analysis on AWD from 56 studies and concluded that mild AWD reduced water use by 23.4% compared with CF. The IAWD treatment in our study reduced total water consumption by 18.4% in 2016 and 7.9% in 2017, relative to the CF treatment. Additionally, IAWD increased WUE compared with CF in both years (Table 3), due to the reduced irrigation water use and comparable grain yield under IAWD.

Zeolite improves WUE by increasing the soil water holding capacity and its availability to plants due to its highly porous structure [52,53]. Many studies have reported that zeolite used as a soil amendment increased soil water retention and reduced deep percolation, thereby reducing water use in agricultural activities [23,54,55]. Prior to this study; however, few studies have been reported on the effect of zeolite on water use in rice [42]. The results herein indicate that zeolite application has no significant effect on irrigation water use (Table 1). In contrast, Sepaskhah and Barzegar [42] reported that zeolite application rates of 4–8 t ha^{-1} reduced water use in rice. The different results may be related to differences in soil properties and experimental environments (paddy field versus lysimeters without percolation). Nevertheless, zeolite application increased WUE by 11.6% (two-year average), relative to the no-zeolite treatment (Table 3), which was mainly attributed to higher grain yield and similar water use with zeolite application. These findings agree with those of Ozbahce et al. [56], and Hazrati et al. [40], who found that the WUE of different plants increased with the application of zeolite.

Phosphorus application had no significant effect on total water use. However, it significantly improved WUE compared with nil-P control (Table 2; Table 3). This could be attributed to an increase in grain yield and comparable water use under P application, which agrees with the findings of Li et al. [57] and Usman [44], who found that phosphorus application improved WUE.

4.3. Effect of Irrigation and Zeolite Application on P Uptake

Soil P availability to plants could be influenced by the irrigation regime [58], which is closely related to the oxidation–reduction condition of soil [59]. It is generally accepted that P uptake by plants declines in drying soil conditions [60]. Ye et al. [61] reported that plant P accumulation declined under AWD, relative to CF, due to the reduction in soil available P under periodic wetting and drying conditions. Similar results occurred in the present study, where the IAWD treatment produced a lower aboveground P uptake than the CF treatment (Table 3). Similarly, Somaweera et al. [62] and Wu et al. [63] reported that shoot P uptake in rice declined under AWD in comparison to CF. The reduction in aboveground P uptake could be attributed to the reduction in soil available P under AWD irrigation (Table 4) since the solubility and mobility of P are much less in unsubmerged soil than submerged soil [64]. Hence, higher fertilizer P requirements are needed for optimum grain yields in rice grown under AWD than under CF [12].

Increasing evidence shows that zeolite mixed with chemical fertilizer applied to soil enhances P uptake in plants [16,65,66], which was confirmed in our study with the increases in soil available P and APU in zeolite-amended soil (Table 3; Table 4) and consistent with the results of Hua et al. (2006) [67] and Li et al. [68]. In the present study, the positive effect of zeolite on soil P availability might be related to the amelioration of soil pH and decrease of the exchangeable soil Al, which result in less P being fixed by metal oxyhydroxides [21]. Moreover, Pickering et al. [16] reported that phosphate rock applied in combination with NH_4^+-saturated zeolite greatly enhanced P uptake in sunflowers, due to an increase in soil available P, which is explained by the following Equation described by Allen et al. (1993) [69]:

$$\text{Phosphate rock} + NH_4^+\text{−zeolite} \leftrightharpoons Ca^{2+}\text{−zeolite} + NH_4^+ + PO_4^{3-} \quad (3)$$

The above reaction shows that zeolite, as an ammonium exchanger, reacts with phosphate rock, takes up Ca^{2+} from phosphate rock, and induces dissolution of phosphate rock and the release of P into the soil solution. The effect of NH_4^+-saturated zeolite combined with phosphate rock in paddy field needs to be evaluated in the future. In 2016, the increase in available soil P induced by zeolite under P_{60} was greater than under P_0, regardless of irrigation regime, which suggests that zeolite was more effective at enhancing soil available P with phosphorus application. Therefore, zeolite applied with a low rate of fertilizer P may achieve comparable P uptake and grain yield in rice, as a higher rate of fertilizer P. The effect of zeolite is greater in coarse-textured soils than in fine-textured soils [22]. As the effect of zeolite would vary with the cation exchange capacity and physio-chemical properties of the soil, results from one type of soil in the present study may not be conclusive enough to confirm the findings. Consequently, the interaction of soil type with zeolite, phosphorus, or irrigation regimes should be taken into consideration to further confirm the findings of this study. Zeolite is an eco-friendly material which has been extensively reported to improve physio-chemical properties of soil, due to its unique characteristics of high cation exchange capacity, large internal porosity, and uniform particle size distribution [70]. Zeolite application in the soil has no harm to the natural environment; inversely, it could alleviate not only non-point pollution by reducing nitrate leaching [41] but also trap heavy metals through reducing their bioavailability and prevent their transfer into the food chain [71]. Moreover, soil amended with zeolite was reported to reduce greenhouse gas emission due to its adsorption potential for CO_2 and reducing the effect on N_2O, which is due to its affinity for NH_4^+ [72]. Accordingly, the zeolite application will have great environmental benefits in agricultural production.

5. Conclusions

In this study, the IAWD treatment reduced water use, maintained grain yield, and improved WUE in rice, relative to the CF treatment. Applications of zeolite or phosphorus alone increased WUE, soil available P, aboveground P uptake, and grain yield of rice but had no significant effect on water use. The increase in grain yield induced by zeolite could be attributed to an increase in aboveground P uptake of rice. The combination of zeolite, P, and IAWD produced the highest WUE. Additionally, zeolite application increased NH_4^+-N retention in the topsoil and decreased NO_3^--N leaching in deeper soil layers. Application of zeolite could help reduce the use of P fertilizer in the paddy field, with benefits for remaining P supplies and mitigating pollution. Thus, the application of zeolite and phosphorus in combination with IAWD irrigation shows promise for reducing water use, increasing rice grain yield, and alleviating environmental risks by reducing N losses.

Author Contributions: Conceptualization—D.C. and T.C.; Methodology—T.C. and Q.W.; Software—T.C. and J.Z.; Investigation—J.Z. and G.L.; Resources—W.C. and W.M.; Data curation— J.Z.; Writing—original draft preparation—J.Z.; Writing—review and editing—J.Z., Y.C. and K.H.M.S.; Supervision—D.C., T.C. and K.H.M.S.; Project administration—D.C., T.C. and G.X.; Funding acquisition—D.C. and T.C.

Funding: This study was funded by the National Natural Science Foundation of China (Grant Nos. 51709173, 51679142), and the Special Fund for Agro-scientific Research in the Public Interest of China (Grant No. 201303125).

Acknowledgments: We greatly appreciate the Chinese Scholarship Council (CSC) for providing a joint PhD student scholarship to J.Z and the travel support to The University of Western Australia.

Conflicts of Interest: The authors declare no conflict of interest.

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