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Can Potassium Silicate Mineral Products Replace Conventional Potassium Fertilizers in Rice–Wheat Rotation?

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ABSTRACT

Potassium (K) silicate minerals are important insoluble K resources and exploring their potential as alternatives to conventional K fertilizers would be helpful to deal with the widespread K deficiency in the world. Thus on-farm experiments with potassium silicate mineral products (KSMPs), e.g., Fubang (FB), Zhongke (ZK), Ziguang (ZG)—manufactured from natural K-bearing rocks—were conducted to investigate their effects on crop yield, soil K fertility and pH in rice-wheat (Oryza sativa L.–Triticum aestivum L.) rotation at Guangde County and Jiangdu County, China. The experiments lasted 2 yr at two sites and six treatments about K fertilizers were tested: no K fertilization (CK); 100% K chloride (KCl); 100% ZG; 50% KCl +50% ZG; 50% KCl +50% FB; 50% KCl +50% ZK. Results showed that both wheat and rice grain yields for CK were markedly decreased compared with that for the other treatments, regardless of K fertilizer types. Similar to KCl, the KSMPs could maintain crop yields and soil potassium fertility. Besides, the KSMPs significantly improved soil pH by average 0.47 and 0.38 at Guangde and Jiangdu, respectively, compared with that for KCl, after its application for 2 yr. However, the apparent K balances for most treatments at two sites were negative. In terms of economic aspect, the value cost ratio averaged by sites of ZG was 2.59 which was significantly higher than that for FB and ZK. In conclusion, the KSMPs can sustain crop yields and soil K fertility and thus can partly substitute conventional K fertilizers in rice-wheat rotation on the Aquic Haplanthrepts soils.

Core Ideas

- We assessed the effects of several mineral fertilizers on crop yield and soil potassium fertility.
- The mineral fertilizers could maintain crop yield and soil potassium fertility.
- The mineral fertilizers could increase soil pH.
- The mineral fertilizers can partly replace conventional potassium fertilizers.

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Potassium (K) plays an important role in plant growth and yield development (Cakmak, 2005; Qiu et al., 2014; Wang and Wu, 2013; Zorb et al., 2014), thus insufficient K supply usually causes serious yield decrease and quality declining. Unfortunately, large agricultural areas of the world including 3/4 of the paddy soil in China and 2/3 of the wheat belt of Southern Australia have gone through K depletion (Römheld and Kirkby, 2010; Zorb et al., 2014), which threatens the world food security. Essentially, insufficient K input is the predominant reason for soil K deficiency. And the inadequate K fertilization is mainly caused by the underdeveloped economy and the scarce soluble K resources (Mohammed et al., 2014). It is well known that soluble K resources are unevenly distributed in the world (Manning, 2015). For most developing countries where the soluble K resources are limited, the high price of the K fertilizers seriously hinders the application of K. Thus exploring alternative K resources for the conventional ones is an urgent task for these countries (Ciceri et al., 2015; Manning, 2010).

Though the soluble K resources are dominated by a few countries, the insoluble ones, such as K feldspar, mica, nepheline, are relatively widely spread in the world (Manning, 2010). The K involved in these resources can be slowly released under the effects of weathering, soil microorganism, and plant root exudates, and consequently, be used by plants. Consequently, it is prudent to explore the potential of these resources as alternatives for conventional K fertilizers. The fertilizer products manufactured from these K-bearing rocks, such as granite, nepheline-bearing rock, feldspar, are defined as K silicate mineral products (KSMPs) in this paper. Many studies have addressed the ability of different KSMPs to yield K under laboratory and pot trial conditions. The K yielding greatly relies on the reacting surface area of the mineral, however, it is difficult to determine it (Manning, 2010). It has been found that nepheline's dissolution rate exceeds that of K feldspar by as much as 100 times at a given pH.

On the other hand, a number of studies have investigated the effects of insoluble K resources on plant growth and yield. For instance, in the 6-mo pot trials (K application rate: 25 g box^{-1}), Bakken et al. (1997) found that the Italian ryegrass

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Abbreviations: EPRY, economic profits from relative yield; FB, Fubang; KSMP, potassium silicate mineral product; KUE, potassium utilization efficiency; VCR, value cost ratio; ZK, Zhongke; ZG, Ziguang.

Table 1. Basic properties of the soils at Guangde and Jiangdu.

Site	Soil texture	Sand	Silt	Clay	Total N	Available P	Total K	HNO_3–extracted K	NH_4OAc-extracted K	Soil organic matter	pH	CEC†
		%			g kg^{-1}	mg kg^{-1}	g kg^{-1}	mg kg^{-1}		g kg^{-1}		mmol$_c$ kg^{-1}
Guangde	Silt loam	17.0	69.1	13.9	1.30	21.2	10.9	290	89.2	24.5	5.22	114
Jiangdu	Silty clay loam	5.20	62.8	32.0	2.27	18.8	7.79	479	102	38.9	5.58	271

† CEC, cation exchange capacity.

(*Lolium multiflorum*) supplied with nepheline-bearing mineral (1% feldspar, 18% nepheline, and 80% biotite; 3.2% K) could assimilate a similar amount of K compared with that supplied with KCl, but the ryegrass treated with K-feldspar-bearing minerals (77–80% K-feldspar; 6.3–6.4% K) achieved a lower K uptake which was similar to the control. Same findings were also attained on grass plants with a wide range of soil types by Bakken et al. (2000) in field trials when the K silicate minerals were applied at a rate of 50 kg ha^{-1}. Recently, increase in rapeseed (*Brassica napus* L.) yield (Zhang et al., 2013) and rice yield (Wang et al., 2014; Zhang et al., 2016) have been reported with the application of K silicate mineral product of Ziguang (ZG) in pot trials.

The above studies showed negative results about K feldspar, however, the positive effects about the K-feldspar were also reported. Abdel-Mouty and El-Greadly (2008) found that okra (*Abelmoschus esculentus* L.Moench) pod yield increased significantly with K-feldspar compared with a control. Aisha and Taalab (2008) found that when feldspar (11.0% K_2O) was applied combined with potassium sulfate (1:1), onion (*Allium cepa*) yield showed no difference compared with using potassium sulfate only. However, the insoluble K sources are still not widely used in the farmland.

The Yangtze River Basin where the dominant cropping system is rice-wheat rotation is one of the main food production and high-yield areas in China, thus the K circulation is more active and the K demand is higher than any other regions. Undoubtedly, it is more necessary to explore the effects of the insoluble K resources on crop yield and soil K fertility in these areas. Although there are studies about the effects of K-bearing silicate minerals on crop yield and soil fertility, most of them were conducted in greenhouse conditions (Zhang et al., 2013; Wang et al., 2014; Zhang et al., 2016). In addition, how the K silicate mineral products (KSMPs) influence the soil properties and food crop yields in varied sites and years are also unknown. Our hypothesis is that the KSMPs used in this study could maintain crop yields and soil K fertility in the rice-wheat rotation, regardless of sites and growing years. Thus, the purposes of this study were to (i) explore the effects of KSMPs on rice and wheat yields, (ii) study the impacts of KSMPs on soil K content and pH and (iii) give some advice on KSMPs application.

MATERIALS AND METHODS

Experimental Design

Field experiments were conducted during 2013 to 2015 at two sites: Guangde County of Anhui Province (31°01′ N, 119°26′ E) and Jiangdu County of Jiangsu Province (32°32′ N, 119°48′ E). The soils at both sites all belong to Aquic Haplanthrepts (Soil Survey Staff, 2014). The soil was silt loam (sand 17.0%, silt 69.1%, clay 13.9%) and silty clay loam (sand 5.20%, silt 62.8%, clay 32.0%) at Guangde and Jiangdu, respectively (Table 1). At Guangde and Jiangdu, soil total nitrogen was 1.30 and 2.27 g kg^{-1}, available P was 21.2 and 18.8 mg kg^{-1}, total K was 10.9 and 7.79 g kg^{-1}, nitric acid-extracted K was 290 and 479 mg kg^{-1}, ammonium acetate-extracted K was 89.2 and 102 mg kg^{-1}, soil organic matter was 24.5 and 38.9 g kg^{-1}, and pH was 5.22 and 5.58, respectively. Guangde and Jiangdu both experience a subtropical humid climate. The perennial rainfall and temperature are 1197 and 1080 mm, and 15.8 and 15.7°C for Guangde and Jiangdu, respectively. The annual average rainfall, temperature and number of sunny days during the experimental period were 1424 mm, 16.4°C, and 139 d for Guangde, and 1541 mm, 16.9°C, and 180 d for Jiangdu, respectively (Fig. 1).

The three kinds of KSMPs used in this study were manufactured from natural K-bearing rock resources and brought from Shanxi Fubang Fertilizer Co. Ltd. (the product is hereafter “FB”), Zhongke Jiancheng Mineral Technology Co. Ltd. (“ZK”), and Shaanxi Ziguang Potassium Industry Co. Ltd. (“ZG”). The total K, available K, Ca, Mg, and Si contents as well as the CEC, pH, and mineralogical composition of each KSMP were given in Table 2.

Randomized block design with four replications was used in this study and each plot was 4 m wide and 5 m long. The treatments were: (i) without K fertilizer (CK), (ii) potassium chloride as K fertilizer (KCl), (iii) ZG as K fertilizer (ZG), (iv) 50% KCl + 50% ZG as K fertilizer (1/2 ZG), (v) 50% FB + 50% KCl as K fertilizer (1/2 FB) and (vi) 50% ZK + 50% KCl as K fertilizer (1/2 ZK). The reason why we set the 50% KSMPs + 50% KCl is that it can guarantee sufficient K for the crop at its earlier growing stages. The N and P fertilizers used during the experimental period were urea (N, 46%) and calcium superphosphate (P_2O_5, 12%), respectively. The local recommended K fertilization rates are 90 and 140 kg ha^{-1} for wheat and rice, respectively. In this study, we set the K application rates as 150% of the recommended K rates so as to highlight the effect of K. Thus the fertilizer rates applied were (all in kg ha^{-1}): 210 N, 135 P_2O_5 and 135 K_2O during the wheat season; and 210 N, 135 P_2O_5 and 210 K_2O during the rice season. The application rates of KSMPs were based on the total K content in Table 2. Until the end of the experiment, the total amount of KSMP supplied for each plot was 5.93, 2.97, 10.8, and 9.56 kg for ZG, 1/2 ZG, 1/2 FB, and 1/2 ZK, and accordingly, the total price was 7.42, 3.71, 32.3, and 28.7 yuan. The P, K fertilizers were broadcast as base fertilizer. As for N fertilizer, urea was broadcast at sowing, tillering and jointing in split applications (with a ratio of base-N to topdress-N of 1:0.75:0.75). The wheat and rice cultivars used for the experiments were Yangmai 20 and Wuyunjing 24, respectively. Wheat was planted through broadcast sowing in late October with a seed rate of 188 kg ha^{-1} and harvested in late May. Rice was transplanted four seedlings per hole with a line spacing of 25 cm and a row spacing of 13 cm and harvested in early October. The field experiment lasted for

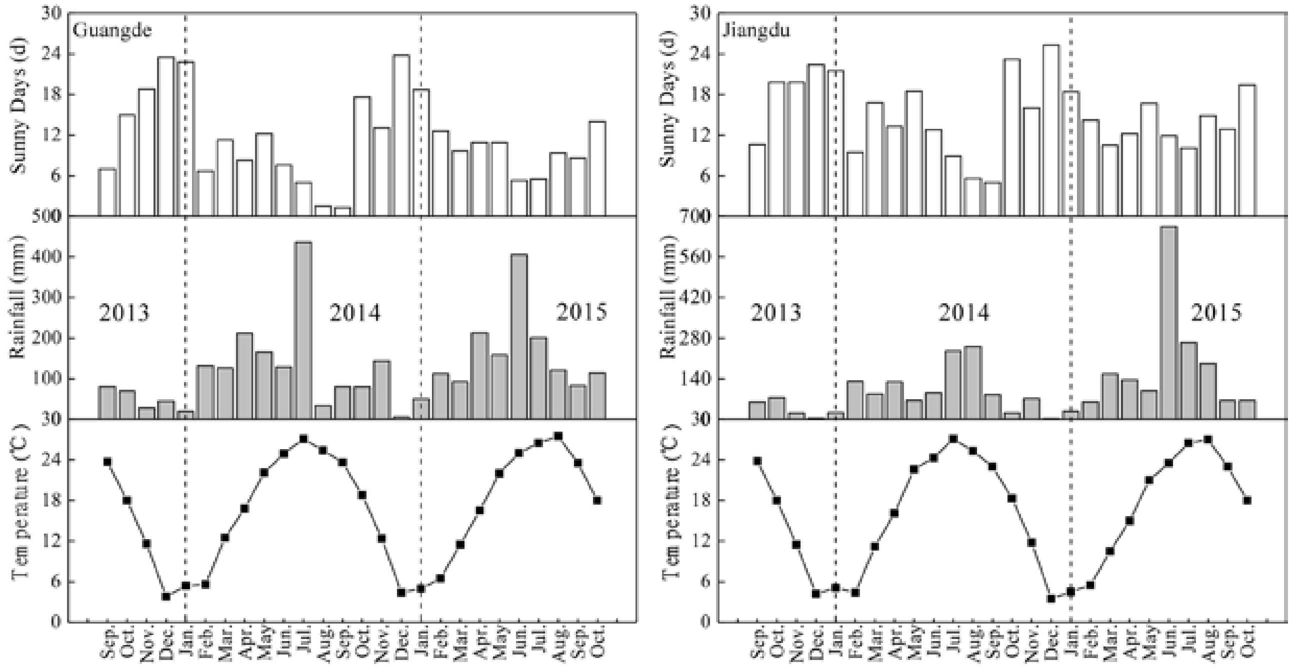

Fig. 1. Monthly mean rainfall and mean temperature in Guangde and Jiangdu from 2013 to 2015

2 yr, from November 2013 to October 2015, including two rice seasons and two wheat seasons.

Sample and Laboratory Procedures

All the crop of each plot was harvested to evaluate the biomass and grain yield when the crop matured, and the aboveground plant material was divided into grain and straw. The plant samples were heated in an oven at 105°C for 30 min and then dried to a constant weight at 70°C. The grain and straw samples were comminuted to determine nutrient concentration. The initial topsoil (0–20 cm) samples were collected just after rice harvest and soil preparation but before fertilization in October 2013 and the other soil samples were collected just after rice harvest but before soil preparation in October 2015 using a soil sampler. Four soil cores (5 cm diameter) were collected in each plot and mixed well as a single soil sample. Soil samples were air-dried at room temperature and ground to pass a 2-mm sieve for further analysis.

The plant samples were digested through the H_2SO_4–H_2O_2 method to determine the K concentration with a flame photometer. Soil total N was determined by the Kjeldahl method (Sparks et al., 1996). Soil available P was extracted with 0.5M $NaHCO_3$ (pH = 8.5), with the volume to weight ratio of 1:20. Total K was determined using the digestion solution of soil treated with Hydrogen Fluoride, perchloric acid, and hydrochloric acid. Ammonium acetate (NH_4OAc, pH = 7.0) was used to extract soil rapid available K (NH4OAc-extracted K). Soil available K (including rapid available K and slow available K) was extracted with 1 M nitric acid boiled for 10 min (detailed procedure in Analytical Methods of Soil Agrochemistry [Lu, 1999]). Soil organic carbon was determined by the potassium dichromate combustion method (Yeomans and Bremner, 1988). Soil pH was measured in a 1:2.5 soil/water suspension (Sparks et al., 1996). As for the KSMPs, the total K, NH_4OAc-extracted K and pH were determined using the same method applied to soil samples. In addition, the water-soluble K was extracted with distilled water with water to fertilizer ratio (v/w) of 10:1 shaking for 30 min and determined by a flame photometer. The citric acid-soluble K, calcium (Ca), (magnesium) Mg, and (silicon) Si was measured following the procedure of determining the P content of fertilizers (Lu, 1999). In brief, weight 1.00 g KSMP into a 250-mL conical flask, then add 100 mL citric acid solution (2%, w/w) into the flask, after that shaking the flasks for 30 min at a speed of 140 rpm. When the extracting process is finished, filter the mixture in the flask

Table 2. Basic properties of the potassium silicate mineral products (KSMPs) of Fubang (FB), Zhongke (ZK), and Ziguang (ZG) that manufactured from natural K-bearing rocks.

	ZG	FB	ZK
Total K(%)	19.3	5.32	5.99
Water soluble K (%)	1.53	1.03	2.52
Exchangeable K (%)†	0.19	0.04	0.24
Non-exchangeable K (%)‡	14.0	3.00	1.43
Citric acid soluble Ca (%)	0.16	11.3	11.4
Citric acid soluble Mg (%)	0.02	0.36	1.74
Citric acid soluble Si (%)	23.2	18.0	24.6
pH	10.2	9.93	12.1
CEC (mmol$_c$ kg^{-1})	52.8	61.5	555
Feldspar (%)	1.00	3.00	37.0
Biotite (%)	53.0	ND§	ND
Kaliophilite (%)	46.0	72.0	ND
Phlogopite (%)	ND	25.0	ND
Calcite (%)	ND	ND	22.0
KCl (%)	ND	ND	4.00
Mullite (%)	ND	ND	21.0
Magnesite (%)	ND	ND	16.0

† Exchangeable K was calculated by NH_4OAc-extracted K minus water-soluble K.

‡ Non-exchangeable K was calculated by HNO_3–extracted K minus NH_4OAc-extracted K.

§ ND, not detected.

Table 3. Analysis of variance of grain yields, straw yield, grain K content, and straw K content among K fertilizer treatment (F), observation year (Y), and site (S).

Variance source	Grain yield		Straw yield		Grain K content		Straw K content	
	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice
S	***	***	***	***	**	*	***	NS†
Y	***	***	***	NS	***	NS	NS	***
F	***	***	***	**	NS	NS	***	***
S × Y	NS	**	NS	***	*	***	***	***
S × F	***	**	*	NS	**	NS	**	NS
Y × F	***	NS	***	**	*	NS	***	NS
S × Y × F	***	**	*	NS	**	NS	***	NS

* Significant at $P < 0.05$; ** Significant at $P < 0.01$; *** Significant at $P < 0.001$.

† NS, not significant.

and measure the contents of Ca, Mg, and Si in the filtrate by inductively coupled plasma–atomic emission spectrometry.

Data Analysis

Potassium utilization efficiency (KUE) was calculated as the ratio of the difference in crop K uptake between treatment with K fertilizer and treatment without K fertilizer to the total K application rate. The economic profits from relative yield (EPRY) were calculated as the difference of the total economic profit for 2 yr between CK treatment and other treatment. The value cost ratio (VCR) was calculated as the ratio of the total economic profit to the total cost of K fertilizer for 2 yr.

Both two-way and three-way analysis of variance (ANOVA) were used to analyze the effects of K fertilizer treatment (Fertilizer), experimental site (Site), and observation year (Year) on crop grain yield, straw yield, plant K content, and other parameters. In the three-way ANOVA, Fertilizer, Site, and Year were entered as fixed factors. The data gained from the experiment were analyzed with Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) and SPSS 22.0 software (SPSS Inc., Chicago, IL). The charts were drawn with OriginPro 2017 software (OriginLab Corporation, Northampton, MA). Mean values of the variables in each treatment were compared using Duncan's test at the 5% probability level.

RESULTS

Grain Yield, Straw Yield, and Plant K Concentration

There was a significant Year × Site × Fertilizer interaction ($p < 0.01$) on both wheat and rice grain yield (Table 3). Thus two-way ANOVAs were conducted at two levels of Year, and it was found that Fertilizer, Site, and Fertilizer × Site significantly affected crop yields (Table 4). In 2014, the crop yields for CK treatment were notably decreased relative to KCl at both sites.

Table 4. Crop grain yield, straw yield (Mg ha^{-1}) as affected by K fertilizer treatment (F), observation year (Y), and site (S). Potassium silicate mineral products of Fubang (FB), Zhongke (ZK), and Ziguang (ZG) were manufactured from natural K-bearing rocks. Treatments were without K fertilizer (CK), potassium chloride as K fertilizer (KCl), ZG as K fertilizer (ZG), 50% KCl + 50% ZG as K fertilizer (1/2 ZG), 50% FB + 50% KCl as K fertilizer, and 50% ZK + 50% KCl as K fertilizer (1/2 ZK).

Year	Treatment	Wheat grain yield		Rice grain yield		Wheat straw yield		Rice straw yield	
		Guangde	Jiangdu	Guangde	Jiangdu	Guangde	Jiangdu	Guangde	Jiangdu
					Mg ha^{-1}				
2014	CK	4.81 d†	4.37 c	7.85 c	8.34 c	4.51 c	4.29 b	7.25 b	12.3 a
	KCl	5.01 c	4.54 bc	8.11 c	8.95 a	5.02 b	4.42 b	8.03 ab	13.1 a
	ZG	5.47 a	4.59 b	9.04 a	8.74 b	5.33 a	4.38 b	8.86 a	12.9 a
	1/2 ZG	5.22 b	4.55 b	8.04 c	9.08 a	5.27 ab	4.70 ab	7.49 b	12.9 a
	1/2 FB	4.94 cd	5.08 a	8.75 b	9.07 a	4.99 b	4.89 a	8.61 ab	12.5 a
	1/2 ZK	5.45 a	5.01 a	7.88 c	8.54 bc	5.57 a	4.97 a	6.25 b	10.6 b
	LSD (P = 0.05)								
	F	0.18		0.26		0.30		1.33	
	S	0.10		0.15		0.17		0.77	
	F × S	0.25		0.37		0.42		NS	
					Mg ha^{-1}				
2015	CK	1.66 c	2.84 d	8.53 c	10.3 b	2.77 c	2.91 c	8.76 b	10.6 a
	KCl	4.16 b	3.34 c	9.61 b	10.7 ab	4.18 b	3.33 bc	10.6 a	10.6 a
	ZG	4.10 b	3.41 c	9.92 ab	10.8 a	4.34 b	3.60 b	10.9 a	10.6 a
	1/2 ZG	4.18 b	3.45 c	9.60 b	10.4 ab	4.39 b	3.58 b	10.7 a	10.2 ab
	1/2 FB	5.15 a	4.04 b	10.1 a	10.4 ab	6.07 a	4.14 ab	10.4 a	9.84 b
	1/2 ZK	3.90 b	4.39 a	9.42 b	10.7 ab	4.30 b	4.55 a	10.8 a	10.7 a
	LSD (P = 0.05)								
	F	0.28		0.42		0.66		0.70	
	S	0.16		0.24		0.38		NS	
	F × S	0.39		0.59		0.94		0.99	

† Different lowercase letters in the same column for the same year mean significant difference ($p < 0.05$).

Table 5. Grain K content (mg kg^{-1}), and straw K content (mg kg^{-1}) as affected by K fertilizer treatment (F), observation year (Y), and site (S). Potassium silicate mineral products of Fubang (FB), Zhongke (ZK), and Ziguang (ZG) were manufactured from natural K-bearing rocks Treatments were without K fertilizer (CK), potassium chloride as K fertilizer (KCl), ZG as K fertilizer (ZG), 50% KCl + 50% ZG as K fertilizer (1/2 ZG), 50% FB + 50% KCl as K fertilizer, and 50% ZK + 50% KCl as K fertilizer (1/2 ZK).

		Wheat grain K content		Rice grain K content		Wheat straw K content		Rice straw K content	
Year	Treatment	Guangde	Jiangdu	Guangde	Jiangdu	Guangde	Jiangdu	Guangde	Jiangdu
		Mg ha^{-1}							
2014	CK	4.50 a†	3.34 ab	2.59 a	2.56 a	10.9 bc	12.2 c	17.8 b	12.7 b
	KCl	3.58 c	3.47 ab	2.95 a	2.61 a	10.2 c	15.7 a	25.9 a	25.2 a
	ZG	3.83 bc	3.36 ab	2.73 a	2.61 a	13.1 a	12.6 c	26.6 a	24.3 a
	1/2 ZG	3.38 c	3.63 a	3.11 a	2.66 a	10.3 bc	14.4 b	27.2 a	26.2 a
	1/2 FB	4.03 b	3.30 b	2.57 a	2.57 a	11.0 b	15.2 ab	27.2 a	24.0 a
	1/2 ZK	3.30 c	3.26 b	2.61 a	2.62 a	9.77 c	14.6 b	25.1 a	23.6 a
	LSD (P = 0.05)								
	F	0.32		NS		0.72		2.59	
	S	0.18		NS		0.42		1.49	
	F × S	0.45		NS		1.02		NS	
		Mg ha^{-1}							
2015	CK	4.02 a	3.61 a	2.26 c	3.02 ab	4.19 d	12.2 c	11.5 c	15.1 b
	KCl	4.06 a	3.69 a	2.80 a	3.17 a	10.8 bc	17.8 a	20.8 a	22.1 a
	ZG	3.41 a	3.91 a	2.58 b	3.06 ab	8.83 c	16.5 ab	21.3 a	22.6 a
	1/2 ZG	3.95 a	3.67 a	2.57 b	2.96 b	12.8 a	15.7 b	21.6 a	22.0 a
	1/2 FB	3.96 a	4.06 a	2.60 b	2.75 c	9.84 c	17.0 ab	21.7 a	21.5 a
	1/2 ZK	3.91 a	4.01 a	2.50 b	2.95 b	11.3 b	15.9 b	19.7 b	21.7 a
	LSD (P = 0.05)								
	F	NS		0.17		1.42		1.38	
	S	NS		0.10		0.82		0.79	
	F × S	0.44		0.24		2.01		NS	

† Different lowercase letters in the same column for the same year mean significant difference (p < 0.05).

CK significantly decreased the wheat yields at both sites and the rice yields at Guangde compared with KCl treatments in 2015. The crop yields for KSMPs were significantly higher or no less than that for KCl at both sites in 2 yr. For most treatments, wheat yields in Guangde were significantly higher than those in Jiangdu, but rice yields in Gaungde were notably lower than those in Jiangdu.

There was also a significantly Year × Site × Fertilizer interaction on wheat straw yield, whereas the two-way interaction of Year × Fertilizer significantly influenced the rice straw yield (Table 3). The wheat straw yield for CK was significantly decreased compared with that for most of the treatments with K fertilization at both sites and years, regardless of the applied K source (Table 4). As for rice straw yield, no significant reduction for CK was found compared with KCl at both sites in 2014. However, 1/2 ZK markedly decreased the straw yields compared with KCl at both sites in 2014. In 2015, CK caused notable straw yield reduction compared with KCl at Guangde, but no decrease was found at Jiangdu. And no significant difference in rice straw yields was found between KCl and KSMPs in addition to 1/2 FB at Jiangdu. The comparisons for straw yields in two sites showed a similar trend as grain yields.

The Year × Site × Fertilizer interaction was significant on wheat grain K content (Table 3). Without K fertilization, the wheat grain K content for CK was significantly increased compared with that of KCl at Guangde in 2014, but no notable difference was found at Jiangdu (Table 5). And for most KSMPs treatments, the wheat grain K contents showed no marked difference compared with KCl at both sites. However, the wheat grain K contents for all treatments were similar to each other in 2015 at both sites. There were no significant differences for rice grain K contents among all the treatments in 2014 at both sites. Notable reductions in rice grain K content for CK and KSMPs were found compared with KCl at Guangde in 2015. But no marked difference was found in rice grain K content among treatments at Jiangdu except the 1/2 FB which got the lowest rice grain K content.

There was a significant Year × Site × Fertilizer interaction on wheat straw K content, whereas there was a Site × Year interaction on rice grain K content (Table 3). The wheat straw content for CK showed no significant difference compared with KCl at Guangde but was notably decreased at Jiangdu in 2014. Compared with KCl, the wheat straw K content for ZG and 1/2 FB were notably increased but no significant difference was found for 1/2 ZK and 1/2 ZG at Guangde. However, except 1/2 FB, the wheat straw K contents for KSMP were all significantly decreased compared with KCl at Jiangdu in 2014. In 2015, the wheat straw K contents for CK were significantly decreased compared with KCl at both sites. Compared with KCl, no significant decrease was found in wheat straw K content for KSMPs at Guangde, but 1/2 ZG and 1/2 ZK markedly reduced the K content in Jiangdu. The rice straw K contents for CK were significantly decreased compared with that of KCl but no significant difference between KCl and KSMPs was found at both sites in 2 yr except the 1/2 ZK at Guangde in 2015 which notably decreased the straw K content.

Total Plant K Uptake, KUE, and Apparent K Balance

Fertilizer and Site significantly affected total plant K uptake (Table 6). The total plant K uptakes for the treatments supplied with K fertilizer were markedly increased by 55.6 to 88.4% and

Table 6. Total K fertilizer input, total plant K uptake, K utilization efficiency (KUE) and apparent K balance (kg ha^{-1}) as affected by K fertilizer treatment (F) and site (S). Potassium silicate mineral products of Fubang (FB), Zhongke (ZK), and Ziguang (ZG) were manufactured from natural K-bearing rocks Treatments were without K fertilizer (CK), potassium chloride as K fertilizer (KCl), ZG as K fertilizer (ZG), 50% KCl + 50% ZG as K fertilizer (1/2 ZG), 50% FB + 50% KCl as K fertilizer, and 50% ZK + 50% KCl as K fertilizer (1/2 ZK).

		Total K uptake		KUE		Apparent K balance	
Treatment	Total K input	Guangde	Jiangdu	Guangde	Jiangdu	Guangde	Jiangdu
	kg ha^{-1}						
CK	0	354 d†	484 c	– ‡	– ‡	–354	484 d
KCl	573	608 b	777 a	44.3 b	51.1 a	–35.0 b	–204 c
ZG	573	661 a	753 ab	53.6 a	46.9 ab	–88.0 d	–180 bc
1/2 ZG	573	629 ab	768 a	48.0 ab	49.6 a	–56.0 c	–195 c
1/2 FB	573	667 a	741 ab	54.5 a	44.9 ab	–94.0 e	–168 b
1/2 ZK	573	551 c	714 b	34.4 c	40.1 b	22.0 a	–141 a
	LSD (P = 0.05)						
F		44.4		7.82		15.0	
S		25.6		NS		8.75	
F × S		NS		NS		21.2	

† Different lowercase letters in the same column for the same year mean significant difference (p < 0.05).

‡ Not calculated.

47.5 to 60.5% at Guangde and Jiangdu, respectively, compared with CK and the total K uptake in Jiangdu was notably higher than that in Guangde.

The KUEs (K utilization efficiency) differed significantly among treatments at both sites (Table 6). At Guangde, the KUE of the ZG and 1/2 FB was significantly increased by 9.30 and 10.2% compared with the KCl treatment, respectively, but the KUE of 1/2 ZK was notably decreased by 9.90% compared with KCl. Whereas the KUE of KSMPs treatments at Jiangdu showed no marked difference compared with KCl besides the 1/2 ZK of which the KUE was significantly decreased by 10.0%.

The results showed that Fertilizer, Site, and Year significantly influenced the soil apparent K balance (Table 6). The apparent K balance for CK was notably declined compared with that of KCl at both sites. And the difference was significant in apparent K balances between KCl and KSMPs.

Soil K Status and Soil pH

The results showed that the K application significantly affected the soil K status (Fig. 2). The soil K contents for CK extracted by different methods at Jiangdu were notably lower than that for KCl treatments but no significant difference was found at Guangde. Compared with KCl treatment, no significant decrease in soil available K for the KSMP treatments was found.

Soil pH was significantly affected by K fertilizer treatment (Fig. 3). The soil pH for CK at both sites was similar to that of KCl. However, compared with KCl, the soil pH for 1/2 FB and 1/2 ZK treatments was significantly increased by 0.76 and 0.72 in Guangde, respectively, and by 0.60 and 0.48, respectively, in Jiangdu. No significant difference for soil pH was found among KCl, ZG, and 1/2 ZG at both sites.

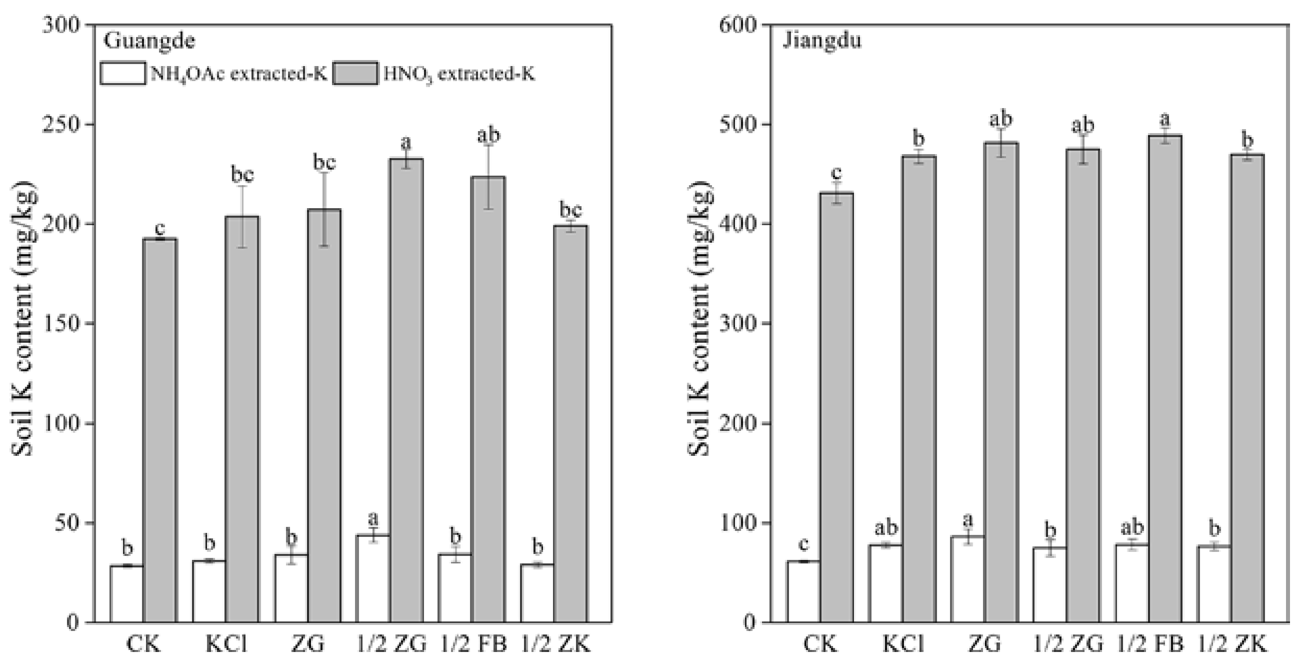

Fig. 2. Soil ammonium acetate (NH_4OAc) extracted-K (water-soluble K + exchangeable K) and nitric acid (HNO_3) extracted-K (water-soluble K+ exchangeable K+ non-exchangeable K) as affected by different K fertilizers at the end of the experiment. Different letters above the columns of the same item mean significant difference (P < 0.05).

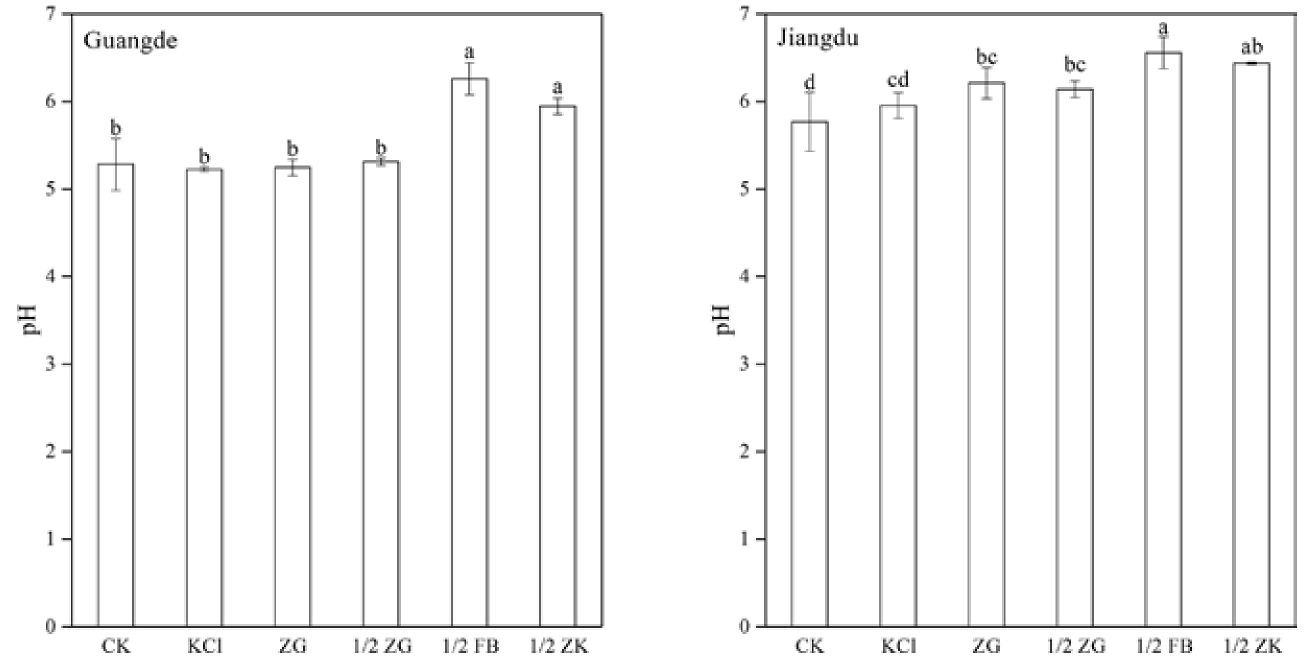

Fig. 3. Soil pH as affected by different K fertilizers. Different letters above the columns mean significant difference ($P < 0.05$).

Economic Profits of Relative Yield and Value Cost Ratio

The EPRY and VCR were significantly affected by Fertilizer, Site, and their interaction (Table 7). The EPRY for KSMPs showed no significant decrease compared with that of KCl at both sites. And the EPRY for ZG and 1/2 FB in Guangde and 1/2 FB and 1/2 ZK in Jiangdu were notably increased compared with that of KCl. The VCRs for ZG in Guangde and 1/2 ZG in Jiangdu showed no significant difference compared with that of KCl. However, the VCR for other treatments were significantly decreased compared with that of KCl.

DISCUSSION

Effects of KSMPs on Wheat and Rice

Potassium is an essential nutrient for crop growth and yield production. Thus K deficiency could cause significant economic losses (Pettigrew, 2008). Our results showed that without K fertilizer application CK suffered significant crop grain yield losses at both sites due to a soil K deficiency (Table 4). Although crop grain yield responses to KSMPs differed across crops, seasons and sites, the KSMPs showed potential to sustain or even increase crop grain yields compared to KCl, which indicated that the K involved in the KSMPs was rather available to wheat and rice. Especially, without combining with KCl, the ZG treatment can achieve a similar or higher crop grain yield compared with KCl. The reasons why the crop grain yield of KSMP treatments could be higher than that of KCl treatment might be: first, the K availability of ZG in soil conditions was similar to KCl; and second, the Ca, Mg, and Si involved in the KSMPs could enhance the crop growth and grain yield development. However, Bakken et al. (2000) found that the K involved in nepheline released extremely slowly and the K involved in feldspar seemed to be nearly unavailable for the grass plants. The reason why our results differed from those previous pot experiments (Bakken et al., 1997; Gautneb and Bakken, 1995; Mohammed et al., 2014) and field experiments (Sanz Scovino and Rowell, 1988) is that, on the one hand, in our study the KSMPs were applied combined with KCl, on the other hand, the producing process of KSMPs may have activated the K involved in the rocks. Nevertheless, our results for ZG were consistent with those studies (Bakken et al., 1997; Gautneb and Bakken, 1995; Mohammed et al., 2014) in which ZG increased the growth of the crop compared with KCl treatment. The effects of KSMPs on crop growth and grain yield were not stable and they may be caused by the differences in climate and soil, which affect the K release pattern of minerals (Li et al., 2015) and K uptake abilities of crops (Glass and Perley, 1980; Pettersson and Jensén, 1983). The results also showed that wheat is more susceptible to K deficiency than rice, which is in agreement with Lu et al. (2017). A similar finding was obtained in a field experiment by Regmi et al. (2002), who owed the wheat

Table 7. Economic profits from relative yield (EPRY) and value cost ratio (VCR) as affected by K fertilizers. Potassium silicate mineral products of Fubang (FB), Zhongke (ZK), and Ziguang (ZG) were manufactured from natural K-bearing rocks. Treatments were potassium chloride as K fertilizer (KCl), ZG as K fertilizer (ZG), 50% KCl + 50% ZG as K fertilizer (1/2 ZG), 50% FB + 50% KCl as K fertilizer, and 50% ZK + 50% KCl as K fertilizer (1/2 ZK).

	EPRY†		VCR	
Treatment	Guangde	Jiangdu	Guangde	Jiangdu
	yuan ha^{-1}			
KCl	10,510 b‡	4,217 b	4.69 a	1.88 a
ZG	14,982 a	4,290 b	4.17 ab	1.19 b
1/2 ZG	10,892 b	4,210 b	3.73 b	1.44 ab
1/2 FB	16,130 a	6,992 a	0.60 c	0.26 c
1/2 ZK	9,829 b	7,178 a	0.35 c	0.25 c
	LSD ($P = 0.05$)			
F	2,139		0.62	
S	1,353		0.39	
F × S	3,026		0.88	

† Mean prices of the KCl, ZG, FB, ZK, wheat, and rice were 1950, 1250, 3000, 3000, 2580, and 2760 yuan Mg^{-1} respectively, from 2013 to 2015.

‡ Different lowercase letters in the same column for the same year mean significant difference ($p < 0.05$).

grain yield reduction to the lower soil K availability in the wheat season compared with the rice season. This may be because irrigation water in this area carries an appreciable amount of K into the plot and K of soil becomes slowly available in a waterlogged situation (Kuchenbuch et al., 1986). In addition, the lower K supply and weakened root nutrient uptake associated with low temperature in winter is also the reason why the wheat yield is more sensitive to K deficiency. The wheat grain yields decreased, whereas the rice grain yields increased in the CK as well as in all treatments in the second year. The decrease in wheat grain yield for the CK treatment was most possibly caused by K deficiency and the rainy weather when it was seeding. For the one hand, K was an essential element for plant growth and yield development, thus the insufficient K supply decreased the wheat yield; on the other hand, excessive rainfall at sowing could decrease the germination rate of wheat and consequently lead to yield reduction (Giri and Schillinger, 2003). The increase in rice grain yield for all treatments in the second year might be caused by the more solar radiation during the rice season in the second year because there were more sunny days from June to October in 2015 (Deng et al., 2015). However, both the rice grain and straw yield for 1/2 ZK in 2014 were lower compared with the other treatments that supplied with K fertilizers. The abnormal rice straw yield in 2014 possibly caused by the different amount of stubble remained in the field. Because at harvest time, the crop was harvested by several farmers using sickles, which led to the different stubble heights and consequently enlarged the crop straw yield difference. On the other hand, the higher content of feldspar in ZK made the weaker solubility of the K involved in it which contributed to the yield reduction of both straw and grain.

The wheat grain K content of the CK treatment is always higher compared with that for the other treatments, this may be induced by the lower yield or biomass which enriched the grain K content (Bai et al., 2015). The K uptake of crops for CK seriously decreased for both sites as a result of soil K depletion (Table 6), and the decreasing magnitude was larger in Guangde than in Jiangdu, which may be caused by the different soil K content (Table 1). The K uptakes of treatments with KSMPs for rice and wheat in Guangde were higher than that of KCl except for the 1/2 ZK, which was in reverse to that at Jiangdu, and this was possibly due to the different soil K status of the two sites.

Effects of KSMPs on Soil Properties

At post-experiment, the NH_4OAc-extracted K for all treatments decreased compared with pre-experiment in both sites, indicating that the soil rapidly available K pool was going through a depletion (Table 1; Fig. 2). The HNO_3–extracted K in Guangde significantly decreased, but showing no distinct difference in Jiangdu, this may be caused by the lower soil K background values in Guangde and more sand content which could lead to more serious K leaching (Wihardjaka et al., 1999). This result was in agreement with the study of Singh et al. (2002) and indicated that the current K application rate would seriously threaten the sustainability of soil fertility. Regardless of fertilizer types, the soil available K for treatments supplied with K was significantly higher than that for CK. It indicated that K fertilization was necessary for sustaining soil K fertility. In addition, the soil available K for KSMP treatments at the end of the experiment were similar to or slightly higher than that for KCl treatment, which indicated that the KSMPs could replenish the K removed by the aboveground plants just as KCl did (Wihardjaka et al., 1999).

The apparent K balances in this study were mostly negative except for the 1/2 ZK treatment in Guangde, though large amounts of K fertilizers had been applied (Table 6). It indicated that the current K application rate could not replenish all the K removed by crops. This also explained the phenomenon that both soil NH_4OAc-extracted K and HNO_3–extracted K at post-experiment were decreased significantly compared with that of pre-experiment. Thus straw return or increasing the K application rates are necessary for sustainable production (Singh et al., 2002; Vitousek et al., 2009; Wihardjaka et al., 1999).

Soil acidification is one of the major challenges for agricultural systems across the world (Guo et al., 2010). Our study showed that the application of KSMPs significantly affected soil pH. The soil pH values were increased for all KSMP treatments at Jiangdu and only 1/2 FB and 1/2 ZK treatments at Guangde to different extents (Fig. 3). It had been reported that soil acidity is created by the removal of bases by harvested crops, leaching, and an acid residual left in the soil from N fertilizers (Fernández and Hoeft, 2009). In the current study, without lime application and crop straw incorporation, lots of alkaline cations were removed by crops. Thus the increase in soil pH in this experiment was most probably caused by the high pH of KSMPs. This indicated that the KSMPs might be more suitable when applied to acidic arable land.

Feasibility of KSMPs to Replace Conventional K Fertilizer

In our study, the KSMPs showed great effects on maintaining crop yield and soil available K levels, which were similar to or even surpass that of KCl. Similar results were gained on rapeseed (Zhang et al., 2013), ryegrass (Bakken et al., 1997) and onion (Aisha and Taalab, 2008). In addition, the KSMPs used in our study were featured with high pH values and a large part of the K involved in them cannot be extracted by water. So they can be used to acid arable land to prevent the soil pH from decreasing and the area with heavy rainfall so as to reduce the K loss. In addition, these KSMPs are rich in interlayer minerals which could provide more exchangeable sites for adsorbing cations (Table 2). Thus the long-term application of KSMPs could improve soil nutrient content and increase soil pH.

However, the disadvantages of KSMPs are also notable. On the one hand, the K contents of most KSMPs were very low, so they must be applied with a larger volume compare with conventional K fertilizers; on the other hand, the price of the KSMPs was much higher than the conventional K fertilizer because of the higher cost of production. Besides, long-term application of KSMPs probably causes soil basification, especially in soil with high pH. In this study, the combined application of ZG and conventional K fertilizers would be a promising way to apply the KSMPs. But as for the FB and ZK, they were more suitable to be used as a soil conditioner as a result of their high prices.

CONCLUSIONS

Several conclusions can be drawn under the current experimental conditions: both KCl and the KSMPs could maintain wheat and rice yields in the rice-wheat rotation cropping system, and the KSMPs can increase soil pH and keep soil K fertility. Thus potassium silicate mineral products can partly or completely replace the conventional K fertilizers and can be applied to acidic soil to deal with the soil acidification.

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