Effect of Silicon Application on Rice Growth and Production Structure

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Abstract This paper studies the effect of silicon on the growth and production structure of rice (*Oryza sativa* L.), and proposes the appropriate applying amount of silicon. The results show that the application of silicon fertilizer to rice can increase specific leaf weight and leaf area index, and improve rice yield by increasing grain number, kernel number and thousand kernel weight. The growth rate of rice yield is 3.45% – 15.69% by applying silicon. In the Jianghan Plain, the applying amount of silicon fertilizer for rice (SiO_2) is recommended at 15 – 30 kg/ha.

Key words Rice (*Oryza sativa* L.), Silicon fertilizer, Growth, Production structure

1 Introduction

Silicon exists in the rice (*Oryza sativa* L.) plant in an amorphous state ($SiO_2 \cdot nH_2O$), and it is mainly opal formed by dehydration of silica gel[1]. The basal application of silicon fertilizer is conducive to rice root absorption, and the silicon absorbed by rice root from outside can enter into the duct via symplast or apoplast. Then it is delivered to various overground rice organs in silicate liquid state, and participates in the formation of different plant tissues[2]. On the leaf epidermal cells, silicon forms " cuticle-Si double layer" cell wall, which can be combined with mesophyll cell into silicified cell, thus increasing the transmittance of scattered light[3]. The leaf is the main organ for the plant to realize photosynthesis and moisture exchange with the outside[4]. Leaf area index is an important agronomic parameter to reflect crop growth and forecast crop yield[5]. Suitable leaf area index during the heading period coupled with its structure is the main symbol of high yield of rice, and the basis for the coordination of sink and source and balanced development of various organs[6]. The application of silicon fertilizer can promote the overground rice growth, and significantly increase the dry matter accumulation on the ground, but the silicon content under different soil background and dry matter effect under different application treatments are different[2]. Zhou Qing *et al.* [7] and Zhang Guoliang *et al.* [8] point out that the main reason for the increase in rice yield through the application of silicon fertilizer is that spike number, kernel number and thousand kernel weight are increased in varying degrees, the kernel number per spike undergoes the largest increase, and there is a trend of first increasing and then decreasing with increasing use of silicon fertilizer. The effects of silicon on rice growth and yield structure have been reported in many studies, but due to difference in region, level of rice production and soil fertility status, the silicon fertilizer has different effects. We carried out study in 2014 in order to explore the effects of silicon fertilizer on rice growth and yield structure under different soil conditions and different application rate in Qianjiang City.

2 Materials and methods

2.1 Basic situation of experiment The experiment was carried out in multiple points with the same program. Three experimental sites were selected, namely Shaogou Team, Yunlianghu Farm (E_1), Group 3 of Jingxi Village, Haokou stock seed farm (E_2), and Group 4 of Huangwan Village, Taifeng Office, Qianjiang City (E_3). The plow layer soil samples were selected before experiment. Based on the method of reference[9 – 11], the analysis includes five items (organic matter, alkali-hydrolyzable nitrogen, available phosphorus, available potassium and pH) and available silicon. The basic situation of each experimental plot is shown in Table 1.

2.2 Experimental design The experiment includes five treatments: applying no fertilizer (Treatment 1, CK); applying 7.5 kg/ha of available silicon (SiO_2) (Treatment 2); applying 15.0 kg/ha of available silicon (SiO_2) (Treatment 3); applying 22.5 kg/ha of available silicon (SiO_2) (Treatment 4); applying 30.0 kg/ha of available silicon (SiO_2) (Treatment 5). The experiment is designed with three replications. The area of each plot is 30 m^2, and the plots are aligned randomly. A single row is irrigated, leaving a 2-m protection line where the conventional cultivation is conducted. The consumption of nitrogen, phosphorus and potassium fertilizer in the plots is designed according to the experimental field nutrient test results, the annual production and management level, and graded indicators of soil nutrient in Qianjiang City[12 – 14]. The

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specific applying amount is shown in Table 2, and zinc fertilizer is applied to all plots (1.65 kg/ha of pure zinc).

Table 1 Basic nutrient status of experimental plots

Experimental code	Experimental sites	pH	Organic matter // g/kg	Alkali-hydrolyzable nitrogen // mg/kg	Available phosphorus // mg/kg	Available potassium // mg/kg	Available silicon // mg/kg
E_1	112.53215 E, 30.27118N	6.8	26	160	35.0	250	87.4
E_2	112.62773 E, 30.36106N	7.0	31	161	19.8	154	113.1
E_3	112.96516 E, 30.41959N	7.5	29	149	13.8	131	74.6

Table 2 Consumption of nitrogen, phosphorus and potassium fertilizer

Experimental code	Nitrogen g/ha	Phosphorus kg/ha	Potassium kg/ha
E_1	172.5	75.0	90.0
E_2	180.0	90.0	105.0
E_3	195.0	90.0	120.0

2.3 Fertilizer for experiment The nitrogen, phosphorus and potassium fertilizers for experiment are urea (N 46%, Hubei Chemical Fertilizer Plant of Sinopec Group), superphosphate (P_2O_5 12%, Hubei Yang Feng Co., Ltd.), and potassium chloride (K_2O 60%, German Potash Company), respectively; the silicon fertilizer is Dali Gui silicon fertilizer (SiO_2 25%, Wuhan Gaofei Agriculture Co., Ltd.); the zinc fertilizer is Dali Xin zinc fertilizer (Zn 30%, Wuhan Gaofei Agriculture Co., Ltd.). Under each treatment, the phosphate, silicon and zinc fertilizers are applied as base fertilizers; 60% of nitrogen fertilizer is applied as base fertilizer, and 40% of nitrogen fertilizer is applied as dressing (half in tillering period and half in booting period); 60% of potassium fertilizer is applied as base fertilizer, and 40% of potassium fertilizer is applied as dressing (in booting period).

2.4 Crop for experiment The crop for experiment is rice from the transplanted paddy shoots. At E_1, the variety selected is Fengliangyou 1528 (jointly selected and bred by Food Crop Research Institute of Hubei Provincial Academy of Agricultural Sciences and Yangtze University), and the planting density is 132300 plants/ha; at E_2, the variety selected is Peiliangyou 986 (selected and bred by Food Crop Research Institute of Hubei Provincial Academy of Agricultural Sciences), and the planting density is 226700 plants/ha; at E_3, the variety selected is Guangliangyou 476 (selected and bred by Food Crop Research Institute of Hubei Provincial Academy of Agricultural Sciences), and the planting density is 222200 plants/ha. It was planted in early May 2014, transplanted in early June 2014, and harvested in late September 2014. Except the different applying amount of fertilizer, other field operation and management practices, such as land preparation, planting, irrigation and pest control, are conducted according to the usual practice in Qianjiang City. It is harvested in each plot and the yield is determined according to the air-dry weight.

2.5 Data collection and processing In each treatment, two plants are randomly taken and all leaves are removed. After the lower end is neatened, ten leaves are randomly selected, and the 10-cm section of the widest part of the ten leaves are extracted, to measure the leaf width L (cm) and dry weight (deactivation of enzymes for 30 min in oven at 105℃, dried to constant weight at 80 ℃, weighed after cooling). W_B is the dry weight of ten 10-cm leaves, and W_A is the dry weight of the remaining part of the leaf. Related formula: specific leaf weight (g/cm^2) $= W_B$ (leaf weight)/unit leaf area ($10 \times 10 \times L$); leaf area per plant (cm^2) $= (W_A + W_B)$/specific leaf weight; leaf area index = leaf area per plant/plant spacing × row spacing. Data are analyzed using Excel 2003.

3 Results and analysis

3.1 Effect of different applying amount of silicon fertilizer on the specific leaf weight of rice Under each treatment, the samples are selected at the rice tillering, jointing and filling stages, respectively, to calculate the specific leaf weight. The results are shown in Table 2. Table 2 shows that overall, the specific leaf weight of rice at the tillering stage is inversely related to the content of available silicon in soil, and the higher the content of available silicon in soil, the lower the specific leaf weight. In terms of the specific leaf weight under Treatment 1 (CK), there are great differences between various experimental points. The specific leaf weight at E_3 is 0.0533 g/cm^2 higher than at E_2, an increase of 74%, and 0.0308g/cm^2 higher than at E_1, an increase of 33%. By comparing the treatments with different applying amount (Treatment 2, 3, 4, 5), it is found that at E_1 with high fertility, with the increasing amount of silicon fertilizer, the specific leaf weight first increases then decreases; at E_2 and E_3 with medium and low fertility, with the increasing amount of silicon fertilizer, the specific leaf weight shows an increasing trend. At E_1, the specific leaf weight under different treatments is 0.0011 - 0.0039 g/cm^2 higher than under CK, an increase of 1.17% - 4.14%; at E_2, the specific leaf weight under different treatments is 0.0101 - 0.0138 g/cm^2 higher than under CK, an increase of 0.14% - 0.19%; at E_3, the specific leaf weight under different treatments is 0.0120 - 0.0297 g/cm^2, an increase of 9.60% - 23.76%. This indicates that the application of silicon has significant effects on the specific leaf weight of rice, and the specific leaf weight increases with the increasing application of silicon. At the jointing stage, the specific leaf weight in various experimental points under CK is similar (0.0961 - 0.0989 g/cm^2), indicating that regardless of soil fertility, the dry matter accumulation of leaves is similar after entering into the jointing stage. By comparing experimental treatments, at E_1 and E_3 with low content of available silicon, the application of fertilizer helps improve the dry matter accumulation of rice leaf, and Treatment 3 makes the best performance; for

E_2 with high content of available silicon, the application of fertilizer will improve the dry matter accumulation of leaf, and with the increasing application of silicon fertilizer, the specific leaf weight of rice first increases and then decreases. At the filling stage, there are great differences in the specific leaf weight under CK between various experimental points, and at E_3, it is 0.0190 g/cm^2 higher than at E_2, an increase of 19%, and 0.0271 g/cm^2 higher than at E_1, an increase of 30%. By comparing various treatments, it is found that at E_1 and E_2, with the increasing application of silicon fertilizer, the specific leaf weight of rice increases first and then decreases, and for the plots with high soil fertility, if the silicon fertilizer is excessively applied, the specific leaf weight will decrease quickly. At E_3, the application of silicon fertilizer is conducive to the accumulation of dry matter in rice leaves, and with the increasing application of silicon fertilizer, the specific leaf weight increases. In various experimental points, there are some differences between various treatments and CK. At E_1, the specific leaf weight under various fertilizer application treatments is −0.0010 − 0.0030 g/cm^2 higher than under CK, an increase of −1.10% − 3.30%; at E_2, the specific leaf weight under various fertilizer application treatments is −0.0031% − 0.0171 g/cm^2 higher than under CK, an increase of −3.13% − 17.25%; at E_3, the specific leaf weight under various fertilizer application treatments is 0.0018 − 0.0209 g/cm^2 higher than under CK, an increase of 1.52% −17.70%. The results show that the application of silicon fertilizer at the rice filling stage can increase the specific leaf weight of rice, but it also plays an inhibiting role; for the plots with medium fertility or above (E_1 and E_2), with the increasing application of silicon fertilizer, the specific leaf weight of rice first increases and then decreases; for the plot with fertility below the average (E_3), with the increasing application of silicon fertilizer, the specific leaf weight of rice continues to increase. The study of Chen Jinhong *et al.* [15] shows that in low silicon soil, with the increasing application of silicon, the dry matter of aboveground rice organs increases to varying degrees. The study of Peng Yingcai *et al.* [16] demonstrates that the mutual restraint between pore density and specific leaf weight seems impossible to unify large specific leaf weight and high pore density, and some Indica rice varieties not only maintain high pore density but have large specific leaf weight, which is consistent with the results of this study.

Table 2 Effect of different applying amount of silicon fertilizer on the specific leaf weight of rice

Treatment	Specific leaf weight during tillering // g/cm^2			Specific leaf weight during jointing // g/cm^2			Specific leaf weight during filling // g/cm^2		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
1(CK)	0.094 2	0.071 7	0.125 0	0.098 4	0.096 1	0.098 9	0.091 0	0.099 1	0.118 1
2	0.095 3	0.081 8	0.137 0	0.095 9	0.095 0	0.099 4	0.093 1	0.116 2	0.119 9
3	0.096 4	0.082 0	0.138 0	0.105 7	0.107 2	0.103 3	0.094 0	0.111 6	0.127 5
4	0.099 7	0.082 3	0.144 3	0.102 0	0.109 8	0.102 3	0.091 5	0.097 0	0.129 7
5	0.098 1	0.085 5	0.154 7	0.102 7	0.092 8	0.104 8	0.090 0	0.096 0	0.139 0

3.2 Effect of different applying amount of silicon fertilizer on rice leaf area inde Crop yields increase as the leaf area index increases. When the leaf area index increases to a certain limit, the yield decreases due to insufficient light and weak photosynthetic efficiency. Under various treatments, the samples are selected at the rice tillering, jointing and filling stages, respectively, to calculate the leaf area index, and the results are shown in Table 3. From Treatment 1 in various experimental points, we see that different planting density and different fertility at the rice tillering, jointing and filling stages have significant effect on the rice leaf area index. For the similar planting density, the higher the fertility, the larger the leaf area index; for different fertility, the higher the planting density, the larger the leaf area index. Different applying amount has obvious influence on the rice leaf index in different period. The rice leaf index and the applying amount of silicon are simulated according to quadratic regression model for fitting the quadratic effect equation of leaf index (y) and applying amount of silicon (x) (Table 4). Table 4 shows that during tillering, the applying amount of silicon fertilizer is poorly fitted with rice leaf index, and the fitting degree is relatively high only at E_1, $R^2 = 0.76$. After entering into the jointing stage, the fitting degree between the applying amount of silicon fertilizer and rice leaf area index is significantly increased, and the fitting degree at E_2 is highly significant, $R^2 = 0.99$. At the filling stage, the overall fitting degree between the applying amount of silicon fertilizer and rice leaf area index is significantly improved, and at E_1 and E_2, $R^2 > 0.95$, indicating that the application of silicon fertilizer in the plots with fertility above average has a parabolic effect on rice leaf area index. Previous findings[5, 17−19] suggest that there is a parabolic relationship between leaf area index at heading stage and yield information, and the correlation is significant, indicating that the leaf area index at the heading stage is one of the main factors affecting yield, and there is a suitable range of leaf area index for high-yielding rice. The leaf area index during tillering is smaller than during transplanting. From the tillering, with growth process, the leaf area index increases and peaks at the booting stage, but then begins to decrease with the aging of plant, and reaches the minimum during the maturity period. After the application of silicon fertilizer to rice, it helps improve the photosynthetic rate. Wei Yonghua *et al.* [20] believe that the appropriate increase of leaf area can promote effective spike number, grain number and kernel number, but also make the thousand kernel weight slightly decrease.

Table 3 Effect of different applying amount of silicon fertilizer on rice leaf area index

Treatment	Tillering stage			Jointing stage			Filling stage		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
1(CK)	1.25	7.13	2.96	4.01	12.05	5.13	3.87	9.81	4.01
2	1.27	7.50	3.58	4.11	12.51	5.23	3.97	11.71	4.04
3	1.53	7.83	3.42	4.23	12.77	5.87	3.98	11.90	4.16
4	1.60	8.27	3.11	3.91	12.75	5.93	3.97	12.25	4.81
5	1.45	7.12	3.05	3.85	12.67	5.39	3.86	11.22	4.39

Table 4 The quadratic effect equation fitting results of leaf area index and the application amount of silicon in different periods

Growth period	Experimental points	Quadratic effect equation	R^2	*F* value
Tillering stage	E_1	$y = 1.198\,3 + 0.029\,9x - 0.000\,7x^2$	0.76	3.13
	E_2	$y = 7.001\,4 + 0.121\,6x - 0.003\,9x^2$	0.70	2.32
	E_3	$y = 3.066\,3 + 0.053\,7x - 0.001\,9x^2$	0.62	1.60
Jointing stage	E_1	$y = 4.017\,4 + 0.022\,0x - 0.001\,0x^2$	0.73	2.73
	E_2	$y = 12.059\,7 + 0.071\,5x - 0.001\,7x^2$	0.99	108.19
	E_3	$y = 5.000\,9 + 0.087\,1x - 0.002\,4x^2$	0.73	2.69
Filling stage	E_1	$y = 3.871\,1 + 0.016\,5x - 0.000\,6x^2$	0.98	41.84
	E_2	$y = 9.891\,7 + 0.261\,9x - 0.007\,2x^2$	0.95	19.48
	E_3	$y = 3.923\,1 + 0.034\,5x - 0.000\,5x^2$	0.56	1.25

3.3 Effect of different applying amount of silicon fertilizer on rice yield structure The seed samples are selected before the rice harvest in the plots, and the results are shown in Table 5. Table 5 shows that at various experimental points, the higher the soil fertility, the greater the effective panicle number. For different applying amount of silicon fertilizer, there are differences in various experiments. At E_1, with the increasing application of silicon fertilizer, the effective panicle number first increases and then decreases; at E_2 and E_3, with the increasing application of silicon fertilizer, the effective panicle number of rice continues to increase. At various experimental points, the grain number under the silicon fertilizer application treatment is higher than under CK. Different applying amount of silicon fertilizer has obvious influence on the rice grain number. At various experimental points, with the increasing application of silicon fertilizer, the grain number is increased to varying degrees. The setting rate is different under different treatments. With the increasing application of silicon fertilizer, the setting rate is increased at E_1, while it first increases and then decreases at E_2 and E_3. The results show that the application of a certain amount of silicon fertilizer can increase the rice setting rate at various experimental points. The application of silicon fertilizer can increase the rice thousand kernel weight, and under the silicon fertilizer application treatment, the thousand kernel weight is 0.1 – 0.3 g higher than under CK. With the increasing application of silicon, the theoretical yield will also increase. By calculation, it is found that at E_1, the theoretical yield under silicon fertilizer application treatment is 7.80% – 14.69% higher than under CK; at E_2, the theoretical yield under silicon fertilizer application treatment is 1.14% – 11.44% higher than under CK; at E_3, the theoretical yield under silicon fertilizer application treatment is 10.02% – 23.47% higher than under CK. This is consistent with the findings of Li Weiguo *et al.* [21], indicating that the application of silicon to rice increases the yield mainly by increasing setting rate, grain number, effective panicle number and thousand kernel weight. From the theoretical yield growth, the lower the soil available silicon content, the greater the potential for increasing yield through the application of silicon fertilizer.

Table 5 The yield structure under different silicon fertilizer treatments

Treatment	Effective panicle number//ear/hill			Grain number grain/ear			Setting rate %			Thousand kernel weight//g			Theoretical yield//kg/ha		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
1	16.9	10.9	8.6	169	152	175	79.65	85.71	86.86	28.0	27.1	27.1	8 452	8 705	7 871
2	17.7	10.9	8.6	171	151	190	80.56	87.02	87.37	28.2	27.2	27.3	9 113	8 805	8 660
3	18.1	11.0	8.8	174	156	191	81.15	86.40	87.43	28.1	27.3	27.4	9 488	9 191	8 947
4	17.9	11.4	8.8	176	160	194	81.85	85.71	88.14	28.2	27.2	27.3	9 617	9 630	9 128
5	17.5	11.4	9.0	179	161	206	83.12	85.53	86.41	28.1	27.2	27.3	9 694	9 701	9 718

3.4 Effect of different applying amount of silicon fertilizer on rice yield The yield is calculated after the rice is mature and harvested, and the results are shown in Table 6. As shown in Table 6, different silicon application treatments at various experimental points play a significant role in increasing rice yield. The yield increase effect of applying silicon fertilizer in the plots with medium or high fertility is larger than in the plots with fertility below the average. With the increasing application of silicon fertilizer, the rice yield in the plots with medium or high fertility first increases and then decreases, while the rice yield in the plots with fertility below the average is also increased. At E_1, the yield is highest under Treatment 4, an increase of 1333 kg/ha (15.32%); the yield is lowest under Treatment 2, an increase of 300 kg/ha (3.45%). At E_2, the yield is highest under Treatment 3, an increase of 1333 kg/ha (15.68%); the yield is lowest under Treatment 5, an increase of 900 kg/ha (10.59%). At E_3, the yield is highest under Treatment 5, an increase of 810 kg/ha (9.68%); the yield is lowest under Treatment 2, an increase of 333 kg/ha (3.98%). The results show that under conditions of moderate silicon fertilizer application, the rice yield is obviously increased, while too high or too low application of silicon fertilizer, the yield will decrease, which is consistent with the findings of Shang Quanyu *et al.*[22] and Zhang Guoliang *et al.*[23]. Through the comprehensive analysis of different types of plots, for the soil with available silicon content around the critical value, the application of silicon fertilizer will effectively increase yield, and the growth rate of yield in the plots with high fertility is higher than in the plots with fertility below the average.

Table Effect of different applying amount of silicon fertilizer on rice yield

Treatment	Plot yield//kg/30 m^2			Equivalent yield//kg/ha			Increase of yield compared with CK//kg/ ha					
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	%	E_2	%	E_3	%
1(CK)	26.10	25.50	25.10	8 700	8 500	8 367	0	0.00	0	0.00	0	0.00
2	27.00	28.40	26.10	9 000	9 467	8 700	300	3.45	967	11.38	333	3.98
3	28.40	29.50	26.63	9 467	9 833	8 877	767	8.82	1333	15.68	510	6.10
4	30.10	28.60	27.13	10 033	9 533	9 043	1 333	15.32	1033	12.15	676	8.08
5	27.45	28.20	27.53	9 150	9 400	9 177	450	5.17	900	10.59	810	9.68

4 Conclusions and discussions

The application of silicon fertilizer to rice can effectively increase the grain number per plant and thousand kernel weight, and obviously improve rice yield. By applying silicon fertilizer, the growth rate of yield in the plots with high fertility is higher than in the plots with low fertility, but with the increasing application of silicon fertilizer, the rice yield first increases and then decreases in the plots with high fertility, while the rice yield continues to increase in the plots with low fertility. Through comprehensive analysis, it is found that the growth rate of rice yield after the application of silicon is 3.45% – 15.68%. Different soil conditions and the application in different periods will have different impact on the specific leaf weight of rice. During tillering, with the same applying amount of silicon fertilizer, the growth rate of specific leaf weight is 9.60% – 23.76% in the plots with low content of soil nutrient and available silicon; at the filling stage, different applying amount of silicon fertilizer can increase or inhibit the specific leaf weight of rice; the specific leaf weight decreases with the increasing application of silicon fertilizer in the plots with medium or high fertility, while the specific leaf weight continues to increase with the increasing application of silicon fertilizer in the plots with fertility below the average. Different planting density and soil fertility have significant impact on the rice leaf area index. During tillering, jointing and filling of rice, for the similar planting density, the higher the fertility, the larger the leaf area index; for different fertility, the higher the planting density, the larger the leaf area index. The application of silicon fertilizer in the plots with different fertility has a parabolic effect on rice leaf area index, the application of silicon fertilizer in the plots with fertility above the average has a parabolic effect on rice leaf area index while the application of silicon fertilizer in the plots with fertility below the average is poorly fitted with rice leaf area index. In Qianjiang City, the available silicon content is in the critical value of 95 – 100 mg/kg[23], and the application of silicon fertilizer can efficiently increase yield. The appropriate applying amount of available silicon (SiO_2) is 15 – 30 kg/ha.

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5 Conclusions

In summary, the transformation risk of scientific and technological achievements concerning tropical agriculture is objective, diverse and comprehensive, and involves all participants. All links interact with each other, and jointly determine the size of the risk. Meanwhile, the transformation risk of scientific and technological achievements concerning tropical agriculture is preventable and controllable. Only by timely, fully and correctly identifying risk can we prevent and avoid many risks, especially legal risk, thus improving the transformation efficiency of scientific and technological achievements concerning tropical agriculture, promoting the development of modern tropical agriculture, increasing farmers income and promoting rural prosperity.

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