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Alleviation of Silicon on Low-P Stressed Maize (*Zea may* L.) Seedlings under Hydroponic Culture Conditions

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Abstract: Using a maize variety sensitive to low-P stress, a hydroponic culture was conducted to study the effect of silicon on photosynthetic characteristics, dry matter accumulation, phosphorus and silicon uptake and accumulation of low-P stressed maize seedlings. It was showed that appropriate Si application to the low-P solution could enhance absorbability and utilization ability of phosphorus in maize seedling roots; increase content and accumulation of phosphorus and silicon, as well as dry matter accumulation in different organs; improve chlorophyll content and net photosynthetic rate of leaves along with root/shoot ratio. These results indicated that appropriate Si application could significantly alleviate the effects caused by low-P stress, which the 1.5mmol/L of Si was considered the optimal got the best effect.

Key words: Silicon · maize · low-P stress · alleviation

INTRODUCTION

The beneficial effects of silicon on plant growth and resistance to biotic and abiotic stress have been proved in higher plants [1-5]. P-deficiency is a typical abiotic stress, which was recognized as a limiting factor for crop growth and output in modern agricultural production [6]. As atom radius, chemical properties and structures of silicon and phosphorus are very similar, consequently have certain interactions [7-9].

Kewei *et al.* [10, 11] indicated that silicon had a significant effect on adsorption and desorption of phosphorus in soils. By a hydroponics experiment, Ma and Takahashi [12] reported that Silicate applications had no significant effects on phosphorus uptake of rice when P-low solution was supplied, while in P-high solution silicate had negative effects on inorganic phosphorus uptake. In a field experiment, Ma and Takahashi [13, 14] also found that when P was low, Silicate applications could not enhance soil P availability and P adsorption of rice but pH and P/Mn ratio in soils, which improved phosphorus utilization efficiency and dry matter of rice plants. Owino-Gerroh and Gascho [15] studied that application of soluble Si in acid soils could decrease adsorption of phosphorus in soils and increase the amount of bio-available phosphorus and soil pH, which improved dry weight and P adsorption of maize. These reports showed different opinions about relationship between Si and P uptake and utilization of crops and principle of alleviation of silicon on low-P stress.

In this paper, a hydroponic culture was utilized to evaluate the effects of different concentrations of Si on accumulation of dry matter, photosynthetic characteristics and uptake of Si and P in low-P stressed maize seedlings. Alleviation of Si on low-P stressed maize seedlings, uptake and accumulation of Si and P in maize were also discussed to provide a theoretical foundation for scientific application of fertilizers on maize in P-deficient areas.

MATERIALS AND METHODS

Plant material and treatments: A low-P-stress sensitive variety of maize (*Zea may L.*), K335 was used in this study. Seeds of K335 were surfacely sterilized for 10min by 15%H_2O_2 and washed and soaked in distilled water for 8 hours. Then, the seeds were transferred on filter papers wetted with distilled water in Petri dishes and germinated at 27°C in incubator. After germination, seeds were sown in cups with gauzes and grew at room temperature. After 4 more days, these seedlings with its basal parts wrapped by absorbent cotton were transplanted into 2 liter pots. The top of pots were sustained by foams, while its

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outside were covered with double dark plastics. Three seedlings per pot were grown with 5 replications.

24 hours after seeding transplantation, the initial distilled water was exchanged for the nutrient solution. The base nutrient solution in this study containing [16]: 2.5 mM $Ca(NO_3)_2$; 1.0 mM K_2SO_4; 0.65 mM $MgSO_4$; 5.0 mM $CaCl_2$; 1.0 μM H_3BO_4; 2.0 μM $MnSO_4$; 1.0 μM $ZnSO_4$; 0.3 μM $CuSO_4$; 0.5 μM $(NH_4)_6Mo_7O_{24}$; 200 μM Fe-EDTA. The nutrient solution was renewed every 3-4 days. Oxygen in nutrient solution was supplied via a air pump for 3¡«4 times a day and 60min each time to keep roots developing well. Plants were grown under controlled environment conditions with a light/dark regime of 14/10h, light/dark, temperatures of 24/18°C, a photo flux density of about 250-300 μmol m^{-2} s^{-1} and a relative humidity of 60-80%.

The 6 treatments on nutrient solution were as follows: ck_1-normal P treatment, base nutrient solution with 1.0 mmol/L P; ck_2-low P treatment, base nutrient solution with 0.001 mmol/L P; Si0.5-low P nutrient solution with 0.5 mmol/L Si; Si1.0-low P nutrient solution with 1.0 mmol/L Si; Si1.5-low P nutrient solution with 1.5 mmol/L Si; Si2.0-low P nutrient solution with 2.0 mmol/L Si. The P source of P nutrient solution was from KH_2PO_4, while the Si from H_4SiO_4. The silicic acid used in this experiment was separated from sodium silicate by cation-exchage resin.

Plant height and dry matter accumulation: After the height measurement of each seedling, the roots, shoots and leaves of each plant were oven dried at 105°C for 30min, separately, followed by another dehydration step under 70°C until in constant weight. The resulting weights were finally measured and recorded.

Chlorophyll content: Leaf samples were treated using an extraction buffer, containing acetone and ethanol with a proportion of 1:1. The content of chlorophyll was measured using colorimetry method [17].

Net photosynthetic rate: Net photosynthetic rate of each samples were tested by LI-6400 portable photosynthesis system (LICOR,USA).

P content of plant: Samples were digested with sulfuric acid-perchloric acid and tested by phosphomolybdate blue spectrophotometry [18].

Si content of plant: Samples were dissolved by dry ashing-HF and then determined by silicomolybdenum blue colorimetric [19].

Statistics: One-way analysis of variance (ANOVA) was conducted to test for effects among treatments, followed by Duncan's multiple range test to compare means between the different trearments.

RESULTS

The effect of Si on dry weight of maize seedlings under low-P stress: The dry weight of different organs in maize seedlings under P-low treatment (ck_2) (Table 1) was significantly lower than that of the normal P treatment (ck_1), which suggested that P-deficiency had obvious effect on the growth and development of maize seedlings. Dry weight of different organs in maize seedlings tended to increase firstly then decrease with increasing Si and the highest amount was the treatment at 1.5 mmol/L Si, which even exceeded the amount of the normal P treatment. Dry weight of root, shoot, leaf and the whole plant of the treatment at 0.5 mmol/LSi were 42.4, 3.62, 14.9 and 16.8% higher than that of the normal P treatment (ck_1) respectively, 135.0, 110.3, 103.8 and 108.9% higher than that of the low P treatment (ck_2), respectively. The above results revealed that appropriate Si could alleviate the effects caused by low-P stress on the growth of maize seedlings and the low-P stress treatment with 1.5 m mol/L Si got the best effect.

The effect of Si on plant weight and leaf number of maize seedlings with low-P stress: The effects of low-P stress also existed in plant weight, unfolded and survived leaf number of maize seedlings (Table 2).

Under low-P stress condition, seedling growth was inhibited; plant became shorter; leaf number reduced; senescence rate of the lower leaf was faster [20]. Nevertheless, appropriate Si application could alleviate all above those symptoms by increasing plant weight, unfolded and survived leaf number and the low-P stress treatment with 1.5 mmol/L Si still got the best effect.

The effect of Si on photosynthesis of maize seedlings with low-P stress: Si application to the low-P solution had a significant effect on chlorophyll content and net photosynthetic rate of maize leaf. Chlorophyll a, chlorophyll b and total chlorophyll contents were raised by appropriate Si application (Table 3).

Chlorophyll content of low-P stressed seedlings with Si applied was significantly greater than that of low-P stressed seedlings without Si applied (ck_2) and normal P treatment (ck_1). The low-P stress treatment with 1.5 mmol/L Si increased to be the biggest and its chlorophyll a, chlorophyll b and total chlorophyll

Table 1: The effect of Si on dry weight of different organs in maize seedlings with low-P stress

	CK1	CK2	Si0.5	Si1.0	Si1.5	Si2.0
Root (g/plant)	0.099b	0.060c	0.064c	0.076c	0.141a	0.081bc
Shoot (g/plant)	0.138a	0.068b	0.074b	0.085b	0.143a	0.086b
Leaf (g/plant)	0.369ab	0.208c	0.214c	0.254c	0.424a	0.295bc
The whole plant (g/plant)	0.606a	0.330b	0.352b	0.415b	0.708a	0.462b
Root/shoot ratio	0.195b	0.217ab	0.222ab	0.224ab	0.249a	0.214b

Note: Lower case letters indicate significant at 5% level, the same below

Table 2: The effect of Si on plant weight, unfolded and survived leaf number of maize seedlings with low-P stress

	CK1	CK2	Si0.5	Si1.0	Si1.5	Si2.0
Plant weight (cm)	56.1a	48.0c	50.6bc	51.6abc	55.9a	54.5ab
Unfolded leaf number	7.000a	5.917c	6.083bc	6.167bc	6.917a	6.333b
Survived leaf number	7.000a	4.833c	5.000c	5.167c	5.917b	5.167c

Table 3: The effect of Si on chlorophyll content and net photosynthetic rate of maize seedlings with low-P stress

	CK1	CK2	Si0.5	Si1.0	Si1.5	Si2.0
Chlorophyll a (mg/g FW)	1.891cd	1.857d	1.916c	1.932bc	2.080a	1.969b
Chlorophyll b (mg/g FW)	0.721c	0.702c	0.772b	0.769b	0.942a	0.800b
Total chlorophyll content (mg/g FW)	2.612cd	2.559d	2.688bc	2.701b	3.021a	2.768b
Net photosynthetic rate (μmol m^{-2} s^{-1})	4.223a	2.603b	2.969b	2.885b	3.941a	2.698b

Table 4: The effect of Si on Si content and accumulation in different organs of maize seedlings with low-P stress

		CK1	CK2	Si0.5	Si1.0	Si1.5	Si2.0
Si content	Root	0.027e	0.000f	0.453d	0.774b	0.536c	1.051a
(mg/g)	Shoot	0.019e	0.006e	0.222d	0.394c	0.655a	0.572b
	Leaf	0.078e	0.088e	0.329d	0.529c	0.788a	0.684b
	Total	0.041e	0.031e	0.335d	0.566c	0.657b	0.769a
Si accumulation	Root	0.003e	0.000f	0.029d	0.059c	0.076b	0.085a
(mg/plant)	Shoot	0.003e	0.001e	0.016d	0.034c	0.094a	0.049b
	Leaf	0.029e	0.018f	0.070d	0.134c	0.332a	0.202b
	Total	0.035e	0.019f	0.115d	0.227c	0.502a	0.336b

contents were 12.0, 34.% and 18.1% higher than that of low-P stress treatment without Si applied separately.

Si application to the low-P solution promoted chlorophyll content and net photosynthetic rate of maize leaf. The average net photosynthetic rate of 4 low-P stress treatments with Si applied was 20.0% greater than that of low-P treatment without Si applied. Furthermore, the net photosynthetic rate of low-P stress treatment with 1.5 mmol/L Si was 51.4% higher than that of low-P stress treatment without Si applied, which was a physiology basis for the reason that Si application could increase dry weight of different organs in maize seedlings.

The effect of Si on Si content and accumulation in different organs of maize seedlings with low-P stress: Si application could enhance not only Si uptake and accumulation of maize seedlings, but also Si content and accumulation in different organs of maize seedlings (Table 4).

Si contents of root, shoot, leaf and the whole plant all raised was increased by increasing Si application to the solution and positive correlation was remarkable between them, which the correlation coefficient were 0.8829, 0.9403, 0.9298 and 0.9622 respectively. Furthermore, the relationship between Si accumulation and Si concentration in the solution differed among different organs. Si accumulation of root promoted with increasing Si concentration and their correlation was significantly positive (R=0.9780). While Si accumulation of shoot, leaf and the whole plant increased firstly then declined with increasing Si concentration and the low-P stress treatment with 1.5mmol/L Si achieved the highest.

Table 5: The effect of Si on P content and accumulation in different organs of maize seedlings with low-P stress

		CK1	CK2	Si0.5	Si1.0	Si1.5	Si2.0
P content (mg/g)	Root	1.172a	0.134d	0.139cd	0.159bc	0.163b	0.150bcd
	Shoot	0.789a	0.156c	0.162c	0.175b	0.178b	0.160c
	Leaf	0.664a	0.150c	0.170b	0.174b	0.173b	0.182b
	Total	0.875a	0.147d	0.157cd	0.170bc	0.171b	0.164bc
P accumulation (mg/plant)	Root	0.116a	0.008d	0.009d	0.012c	0.023b	0.012c
	Shoot	0.109a	0.011d	0.012d	0.015c	0.025b	0.014c
	Leaf	0.245a	0.031f	0.036e	0.044d	0.073b	0.054c
	Total	0.470a	0.050d	0.057d	0.071c	0.121b	0.080c

The effect of Si on P content and accumulation in different organs of maize seedlings with low-P stress: Si application under low-P stress could enhance not only photosynthesis of maize leaf but also P adsorption of maize root (Table 5).

P contents of root and shoot trended to increase firstly then reduce with increasing Si concentration and the low-P stress treatment with 1.5 mmol/L Si reached the greatest; while P content of leaf promoted with increasing Si concentration and their correlation was significantly positive (R=0.8884). Moreover, the relationship between P content of the whole plant(y) and Si concentration(x) significantly fit a quadratic function and the regression equation was $y=0.1476569+0.03422x-0.011125x^2$ ($R^2=0.9882$), so P content of the whole plant got the highest, when Si concentration was about 1.54 mmol/L.

As Si application to the P-deficient solution increased P content and dry matter accumulation of different organs in maize seedlings, P uptake and accumulation also promoted dramatically. The total P accumulation of the whole plant with low-P stress treatment at 0.5 mmol/L Si, 1.0 mmol/L Si, 1.5 mmol/L Si and 2.0 mmol/L Si were 14.9, 42.7, 144.3 and 59.7% greater than that of low-P stress treatment without Si applied and the low-P stress treatment with 1.5mmol/L Si got the biggest. Therefore, Si application could enhance P uptake and utilization and P utilization efficiency of maize seedlings to alleviate the effects caused by low-P stress.

DISCUSSION

Previous studies showed that silicate application could enhance plant growth and dry matter accumulation [3, 13-15]. In our study, when P was low in solution (1000 times lower than normal P concentration), dry weight of different organs in maize seedlings trended to increase firstly then decrease with increasing Si and the highest amount was the treatment at 1.5 mmol/L Si, which even exceeded the amount of the normal P treatment (Table 1). All these indicated that Si with appropriate concentration could promote the growth of maize seedlings, dry matter accumulation of different organs and root/shoot ratio, which could significantly alleviate the effects caused by low-P stress. Therefore, Si application under low-P stress could improve not only the weight of different organs in maize seedlings, but also the dry matter distribution in different organs and dry matter distribution rate in root. The stimulation effect of Si on root was greater than that of shoot and leaf, which promoted the root/shoot ratio to provide a good foundation for strong growth of maize seedlings.

Appropriate Si could not only alleviate chlorophyll decomposition at a certain extent [21], but also enhance absorption of light in leaf. Scatter light transmittance of siliceous cells on leaf surface was 10 times than that of green cells [22], so it could promote photosynthesis for plants [23]. Our experiment suggested that under low-P stress condition, on one hand silicate application alleviated the lower leaf senescence of maize seedlings (Table 2) and increased leaves areas, on the other hand improved chlorophyll content and net photosynthetic rate of leaves (Table 3), which promoted dry matter accumulation of maize seedlings. Therefore, this was the photosynthetic physiology basis of alleviation of silicon on low-P stress.

Different with the results of rice [14, 15], our study indicated that silicate application under low-P stress could enhance not only Si adsorption and its content and accumulation in different organs of maize seedlings (Table 4), but also P adsorption and its content and accumulation in different organs of maize seedlings (Table 5). Positive correlation was remarkable between Si and P accumulation and the correlation coefficient was 0.9683, which showed that Si and P accumulation had a significantly synergistic effect. Therefore, this was the nutritious physiology basis of alleviation of silicon on low-P stress.

Silicate application under low-P stress could enhance not only photosynthesis of maize leaf but also P adsorption of maize root, so appropriate silicate application in P-deficient soils would alleviate the effects caused by low-P stress to promote the growth and development of maize seedlings.

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