# Effects of Combined Silicon and Phosphorus Application on Maize Seedling Growth and Nitrogen, Phosphorus, and Potassium Accumulation: Postprint

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**Date:** 2017-11-09T00:00:00+00:00

## Abstract

Using 'Zhenghong 2' and 'Zhenghong 115' maize as experimental materials and employing sand culture, three pure phosphorus levels [1.0 mmol · L 1 (normal phosphorus level, P1.0), 0.1 mmol · L 1 (moderate phosphorus deficiency, P0.1), and 0.01 mmol · L 1 (severe phosphorus deficiency, P0.01)] and three pure silicon levels [1.5 mmol · L 1 (Si1.5), 0.75 mmol · L 1 (Si0.75), and 0 mmol · L 1 (Si0)] were established. Through the measurement and analysis of dry matter, leaf area, root morphology, and nitrogen, phosphorus, and potassium contents at the maize seedling stage, the effects of combined silicon and phosphorus application on root growth, dry matter accumulation in various organs, and nitrogen, phosphorus, and potassium nutrient accumulation and utilization were investigated, providing a theoretical basis for the rational combined application of phosphorus and silicon fertilizers. The results showed that phosphorus deficiency inhibited maize seedling growth, reduced root length, root volume, root surface area, and leaf area, and decreased the absorption of phosphorus, nitrogen, and potassium as well as dry matter accumulation, with these effects intensifying as phosphorus concentration decreased. Maize adapted to low-phosphorus environments by increasing the root-to-shoot ratio, enhancing the distribution ratio of phosphorus and nitrogen in roots, and improving the dry matter production efficiency of nitrogen, phosphorus, and potassium. The effects of low-phosphorus stress on root growth and phosphorus absorption and accumulation in 'Zhenghong 115' were greater than those in 'Zhenghong 2' , but 'Zhenghong 115' substantially increased the distribution ratio of phosphorus in roots under low-phosphorus conditions. Under normal phosphorus (P1.0) conditions, silicon addition promoted maize root growth, increased phosphorus, nitrogen, and potassium accumulation, enhanced their distribution ratio in shoots, and increased leaf area and dry matter accumulation. Under moderate phosphorus deficiency (P0.1) conditions, silicon addition also increased phosphorus, nitrogen, and potassium accumulation in maize, promoted root and shoot growth, and alleviated low-phosphorus stress. Under severe phosphorus deficiency (P0.01) conditions, increasing silicon application had no significant improvement effect on maize root growth and dry matter accumulation, but increased phosphorus and potassium accumulation in roots. These results indicate that significant synergistic and coordination effects exist between silicon and phosphorus, and they should be applied in combination in production.

## Full Text

## Preamble

**Chinese Journal of Eco-Agriculture**, May 2017, Vol. 25, No. 5: 677-688
ChinaXiv Partner Journal DOI: 10.13930/j.cnki.cjea.170222

### Effect of Combined Phosphorus and Silicon Application on Growth and Nitrogen, Phosphorus, and Potassium Accumulation in Maize Seedlings

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**Abstract:** Using 'Zhenghong 2' and 'Zhenghong 115' maize cultivars in a sand culture experiment, this study examined three phosphorus levels [1.0 mmol·L $^{1}$ (normal phosphorus, P1.0), 0.1 mmol·L $^{1}$ (moderate phosphorus deficiency, P0.1), and 0.01 mmol·L $^{1}$ (severe phosphorus deficiency, P0.01)] and three silicon levels [1.5 mmol·L $^{1}$ (Si1.5), 0.75 mmol·L $^{1}$ (Si0.75), and 0 mmol·L $^{1}$ (Si0)]. By analyzing dry matter, leaf area, root morphology, and nitrogen, phosphorus, and potassium contents at the seedling stage, we investigated the effects of combined silicon and phosphorus application on root growth, dry matter accumulation, and nutrient accumulation and utilization in maize seedlings to provide a theoretical basis for rational phosphorus and silicon fertilizer management. The results indicated that phosphorus deficiency inhibited maize seedling growth, reducing root length, root volume, root surface area, and leaf area, while decreasing phosphorus, nitrogen, and potassium uptake and dry matter accumulation. These effects intensified as phosphorus concentration decreased. Maize adapted to low-phosphorus conditions by increasing the root-to-shoot ratio, enhancing phosphorus and nitrogen distribution in roots, and improving the dry matter production efficiency of nitrogen, phosphorus, and potassium. Low-phosphorus stress affected root growth and phosphorus accumulation more severely in 'Zhenghong 115' than in 'Zhenghong 2', though

‘Zhenghong 115’ substantially increased phosphorus distribution to its roots under low-phosphorus conditions. Under normal phosphorus (P1.0), silicon addition promoted root growth, increased phosphorus, nitrogen, and potassium accumulation, enhanced their distribution to aboveground parts, and increased leaf area and dry matter accumulation. Under moderate phosphorus deficiency (P0.1), silicon also increased phosphorus, nitrogen, and potassium accumulation, promoted root and shoot growth, and alleviated low-phosphorus stress. Under severe phosphorus deficiency (P0.01), silicon application showed no significant improvement in root growth or dry matter accumulation but increased phosphorus and potassium accumulation in roots. These findings demonstrate significant synergistic and coordinated effects between silicon and phosphorus, suggesting that combined application should be practiced in production.

**Keywords:** maize; seedling stage; combined phosphorus and silicon application; nutrient accumulation; nutrient utilization; dry matter accumulation

## Introduction

Maize (*Zea mays* L.) is a crucial food, feed, and energy crop whose stable and high yield is influenced by resources, environmental conditions, and soil nutrient characteristics. While soil testing and formula fertilization have increased soil phosphorus content in recent years, phosphorus-deficient soils remain widespread in production [1-3], requiring substantial phosphorus fertilizer application for grain and oil crops. Continuous increases in phosphorus fertilizer usage have led to reduced phosphorus use efficiency—currently only 11.6% for grain crops in China [4]—and rapid depletion of phosphate rock resources, which are projected to be exhausted within 50 years at current application rates [5]. Maize is a phosphorus-demanding crop highly sensitive to phosphorus deficiency, which is a major factor limiting crop growth and yield improvement in modern agriculture. Some soils have adequate total phosphorus but low available phosphorus, failing to meet crop requirements and causing damage. Phosphorus deficiency reduces organ dry matter accumulation [6], inhibits root growth [7], decreases photosynthetic capacity [8], diminishes nitrogen, phosphorus, and potassium accumulation [9-12], reduces activity of key phosphorus metabolism enzymes [13], and significantly decreases yield [6].

Silicon is a beneficial element for maize and other crops, abundant in the earth’s crust, with structural and chemical properties similar to phosphorus. Maize organs contain approximately 4–75 $\mathrm{g \cdot kg^{1}}$ silicon, and nitrogen, phosphorus, and potassium contents correlate positively with silicon content [14]. Silicon application improves crop uptake of silicon [15] and nutrients including nitrogen, phosphorus, and potassium [16-17], and increases crop yield [18-20]. Due to their similar chemical properties, silicon and phosphorus may exhibit mutually promoting fertilizer effects. Studies suggest silicon can alleviate low-phosphorus stress in maize [21] and improve soil nutrient supply capacity [22-23]. However, it remains unclear whether combined silicon and phosphorus application can promote maize seedling root growth and dry matter accumulation while improving nitrogen, phosphorus, and potassium uptake and utilization. Therefore, this sand culture experiment investigated the effects of combined silicon and phosphorus application on maize seedling growth and nitrogen, phosphorus, and potassium uptake and utilization to provide a theoretical basis for developing efficient nutrient management technologies.

### 1.1 Experimental Materials

The tested maize cultivars were 'Zhenghong 2'and 'Zhenghong 115'[24], provided by Zhenghong Biotechnology Co., Ltd. of Sichuan Agricultural University.

### 1.2 Experimental Design

The experiment was conducted from May to June 2014 in a greenhouse at the Chengdu campus of Sichuan Agricultural University using sand culture. Following Yang et al. [21], a split-plot design was adopted with phosphorus as the main factor at three levels: 1.0 mmol·L$^{1}$ (normal), 0.1 mmol·L$^{1}$ (moderate deficiency), and 0.01 mmol·L$^{1}$ (severe deficiency), designated as P1.0, P0.1, and P0.01, respectively. Silicon concentration served as the subplot factor at three levels: 1.5 mmol·L$^{1}$, 0.75 mmol·L$^{1}$, and 0 mmol·L$^{1}$, designated as Si1.5, Si0.75, and Si0. Each treatment comprised six pots with three replications, totaling 324 pots for both cultivars.

The basal nutrient solution contained: 2.5 mmol·L$^{1}$ Ca(NO ) , 1.0 mmol·L$^{1}$ K SO , 0.65 mmol·L$^{1}$ MgSO , 5.0 mmol·L$^{1}$ CaCl , 1.0  mol·L$^{1}$ H BO , 2.0  mol·L$^{1}$ MnSO , 1.0  mol·L$^{1}$ ZnSO , 0.3  mol·L$^{1}$ CuSO , 0.5  mol·L$^{1}$ (NH ) Mo O  , and 200  mol·L$^{1}$ Fe-EDTA. Phosphorus source was KH PO  and silicon source was Na SiO . Potassium concentration in phosphorus-deficient solutions was supplemented with KCl. The nutrient solution pH was 5.8.

The sand culture substrate was quartz sand (0.5–2 mm) soaked in 10% hydrochloric acid for 3 hours, rinsed with tap water for 20 minutes, washed with distilled water, and placed in pots (20 cm inner diameter, 25 cm height, 7.5 kg sand per pot). Maize seeds were disinfected with 2% sodium hypochlorite for 20 minutes, rinsed with distilled water, soaked for 4 hours, and 15 seeds were sown per pot at 5 cm depth. After sowing, 0.2 L distilled water was applied daily at 9:30 AM and 4:00 PM to ensure uniform emergence. At the two-leaf-one-heart stage, seedlings were thinned to eight uniform vigorous plants per pot.

After thinning, 1 L of different silicon-phosphorus nutrient solutions was applied every two days at 9:30 AM (with 1.5 L distilled water used to moisten the quartz sand before nutrient solution application). After 15 days, the frequency was adjusted.

### 1.3 Measurement Indicators and Methods

Four weeks after applying different nutrient solutions, representative samples were taken for measurement.

**1.3.1 Dry Matter and Leaf Area** Three representative plants per treatment were separated into roots, stem-sheaths, and leaves, oven-dried at 105°C for 30 minutes, then at 80°C to constant weight and weighed (three parallel measurements). Leaf area was measured using the length-width coefficient method (coefficient = 0.75).

**1.3.2 Root Morphology** Roots from the representative plants in section 1.3.1 were analyzed using a root scanner (Epson Expression 1000xl, WinRHIZO software) to determine total root length, total root volume, total root surface area, and average root diameter (three parallel measurements).

**1.3.3 Plant Nitrogen, Phosphorus, and Potassium Contents** Samples from section 1.3.1 were ground after dry weight measurement. Nitrogen content was determined using the Kjeldahl method with concentrated H SO -H O digestion (BUCHI Distillation Unit K-355 + Hanon T860 automatic titrator). Potassium content was measured with an FP6410 flame photometer. Phosphorus content was determined by vanadium molybdate yellow colorimetry. Nitrogen, phosphorus, and potassium accumulation were calculated accordingly.

### 1.4 Data Analysis

Nitrogen (phosphorus, potassium) dry matter productivity ($\text{mg} \cdot \text{mg}^{1}$) = whole plant dry weight (mg) / whole plant nitrogen (phosphorus, potassium) accumulation total (mg) (Equation 1). Data were analyzed using DPS 7.05 software with LSD test for mean comparison.

## 2.1 Effects of Different Phosphorus and Silicon Treatments on Dry Matter, Root/Shoot Ratio, and Leaf Area of Maize Seedlings

As shown in Table 1 , low-phosphorus stress significantly reduced dry matter accumulation and leaf area, with more pronounced reductions in stems and leaves than in roots, thereby increasing the root/shoot ratio. No significant differences in dry matter accumulation or leaf area existed between cultivars, but phosphorus and silicon levels significantly affected dry matter accumulation in each organ and leaf area. The cultivar × phosphorus interaction had no significant effect on dry matter but significantly affected leaf area. Cultivar × silicon interactions showed significant or highly significant effects on both dry matter accumulation and leaf area. Silicon × phosphorus interactions also significantly affected these indicators. The three-way interaction among cultivar, phosphorus, and silicon levels had highly significant effects on whole-plant dry matter and leaf area.

Compared with the control (P1.0), averaging across three silicon levels and two cultivars, moderate phosphorus deficiency (P0.1) reduced stem-leaf and root dry weights by 39.9% and 10.9%, respectively, while increasing the root/shoot ratio by 37.7%. Severe phosphorus deficiency (P0.01) reduced stem-leaf and root dry weights by 42.4% and 26.0%, respectively, while increasing the root/shoot ratio by 20.8%.

Under normal phosphorus (P1.0) and moderate deficiency (P0.1), silicon addition significantly promoted seedling growth, expanded leaf area, and increased dry matter accumulation in all organs. For ‘Zhenghong 2’ under P1.0 and P0.1, Si1.5 and Si0.75 increased whole-plant dry weight by 58.2% and 75.4%, and 4.7% and 5.0%, respectively, compared with Si0. For ‘Zhenghong 115’, the increases were 106.3% and 46.2%, and 31.1% and 9.3%, respectively. ‘Zhenghong 2’ responded best to Si0.75, while ‘Zhenghong 115’ responded best to Si1.5. Under severe phosphorus deficiency (P0.01), adding 1.5 mmol·L$^{1}$ silicon (Si1.5) modestly improved root dry weight of ‘Zhenghong 2’ and stem-leaf dry weight of ‘Zhenghong 115’, whereas Si0.75 showed no effect. Thus, silicon’s growth-promoting effect weakened with decreasing phosphorus concentration, being strongest under normal phosphorus, moderate under moderate deficiency, and weakest under severe deficiency, indicating clear synergistic effects between silicon and phosphorus.

## 2.2 Root Morphological Characteristics of Maize Seedlings Under Different Phosphorus and Silicon Treatments

Table 2 shows that phosphorus and silicon levels significantly affected root length, surface area, average diameter, and volume, with varying effects between cultivars. Some root morphological indicators showed significant interactions for cultivar × phosphorus, cultivar × silicon, silicon × phosphorus, and the three-way interaction. Low-phosphorus stress inhibited root growth, reducing root weight, length, surface area, average diameter, and volume to varying degrees, with greater reductions in ‘Zhenghong 115’ than in ‘Zhenghong 2’. For example, averaging across three silicon concentrations, root surface area of ‘Zhenghong 2’ under P0.1 and P0.01 decreased by 6.3% and 28.1% compared with P1.0, while ‘Zhenghong 115’ decreased by 15.8% and 37.7%, respectively.

Silicon promoted root growth by increasing root length and volume and expanding surface area, particularly under normal and moderately deficient phosphorus conditions, with Si1.5 being optimal for both cultivars. Under severe phosphorus deficiency (P0.01), silicon addition modestly promoted root growth in ‘Zhenghong 2’ but not in ‘Zhenghong 115’. These results demonstrate that silicon application promotes root growth under normal phosphorus, showing good mutual promotion and synergistic effects with phosphorus. Under moderate phosphorus deficiency, silicon application primarily enhances total root length and surface area per plant to improve nutrient uptake and alleviate low-phosphorus stress.

## 2.3 Nitrogen, Phosphorus, and Potassium Accumulation and Distribution in Maize Seedlings Under Different Phosphorus and Silicon Treatments

Table 3 shows that low-phosphorus treatment significantly reduced phosphorus accumulation per plant and affected phosphorus distribution among organs. No significant differences existed between cultivars in total phosphorus accumulation, but significant differences occurred in phosphorus distribution between roots and shoots. Phosphorus and silicon levels significantly affected total phosphorus accumulation and distribution rates. The cultivar × silicon interaction significantly affected total phosphorus accumulation, while cultivar × phosphorus, silicon × phosphorus, and three-way interactions significantly affected all indicators.

Compared with the control (P1.0), 'Zhenghong 2' showed 76.5% and 84.6% reductions in average phosphorus accumulation per plant under moderate (P0.1) and severe (P0.01) deficiency, respectively, while root distribution proportion increased by 40.8% and 37.9%. 'Zhenghong 115' showed 85.4% and 89.0% reductions, with root distribution proportion increasing by 182.9% and 147.3%, indicating greater sensitivity than 'Zhenghong 2'.

Silicon application significantly promoted phosphorus accumulation, with effects strengthening as phosphorus level increased. Under normal phosphorus (P1.0), Si1.5 and Si0.75 increased phosphorus accumulation by 102.8% and 56.1% compared with Si0. Under moderate deficiency (P0.1), increases were 80.1% and 43.1%, respectively. Under severe deficiency (P0.01), increases were only 22.1% and 9.5%. The Si1.5 effect was greater in 'Zhenghong 115', while the Si0.75 effect was greater in 'Zhenghong 2'. Silicon also affected phosphorus distribution, reducing root distribution proportion and increasing shoot distribution proportion under normal and moderately deficient phosphorus conditions.

Table 4 shows that low-phosphorus stress significantly reduced nitrogen accumulation per plant while increasing nitrogen distribution to roots. No significant differences existed between cultivars in total nitrogen accumulation, but significant differences occurred in nitrogen distribution between roots and shoots. Phosphorus and silicon levels significantly affected nitrogen accumulation and distribution. Cultivar × phosphorus and cultivar × silicon interactions significantly affected nitrogen accumulation, while silicon × phosphorus interactions significantly affected both accumulation and distribution. The three-way interaction was also highly significant.

Averaging across three silicon levels and two cultivars, moderate (P0.1) and severe (P0.01) phosphorus deficiency reduced nitrogen accumulation per plant by

52.9% and 56.6% compared with P1.0, while increasing root distribution proportion by 17.7% and 5.7%, respectively. Under normal phosphorus (P1.0), adding 1.5 mmol · L ¹ (Si1.5) and 0.75 mmol · L ¹ (Si0.75) silicon significantly increased nitrogen accumulation by 123.1% and 62.7%, respectively. Si1.5 also increased nitrogen accumulation in 'Zhenghong 115' under moderate and severe phosphorus deficiency, but had no significant effect on 'Zhenghong 2' . Si0.75 showed no significant effect on either cultivar under phosphorus-deficient conditions.

Table 5 shows that the two cultivars did not differ significantly in potassium accumulation per plant, but differed significantly in distribution between aboveground and belowground parts. Phosphorus and silicon levels significantly affected potassium accumulation, while silicon level also significantly affected potassium distribution. Except for the cultivar × silicon interaction on potassium distribution, all other interactions significantly affected potassium accumulation and distribution. Low-phosphorus stress reduced potassium accumulation, though less severely than nitrogen and much less than phosphorus. Averaging across three silicon levels and two cultivars, moderate (P0.1) and severe (P0.01) phosphorus deficiency reduced potassium accumulation by 23.3% and 31.7% compared with P1.0. Phosphorus level also tended to increase root distribution proportion while decreasing stem-leaf distribution.

Under normal phosphorus (P1.0), silicon application significantly increased potassium accumulation and reduced root distribution proportion. Si1.5 and Si0.75 increased average potassium accumulation by 90.5% and 45.9% compared with Si0, while reducing root distribution proportion by 68.7% and 30.3%, respectively. Under moderate phosphorus deficiency (P0.1), Si1.5 also increased potassium accumulation in both cultivars (average increase of 29.8%), but Si0.75 showed no significant effect.

## 2.4 Dry Matter Productivity of Nitrogen, Phosphorus, and Potassium in Maize Seedlings Under Different Phosphorus and Silicon Treatments

Table 6 shows that cultivar, silicon, and phosphorus levels significantly affected nitrogen, phosphorus, and potassium dry matter productivity, with significant or highly significant two-way interactions. Overall, 'Zhenghong 115' had significantly higher phosphorus dry matter productivity (PDMP) than 'Zhenghong 2' , particularly under low-phosphorus stress. Averaging across three silicon levels, PDMP of 'Zhenghong 2'was 13.6%, 47.4%, and 35.2% lower than 'Zhenghong 115' under P1.0, P0.1, and P0.01, respectively. Under severe phosphorus deficiency (P0.01), 'Zhenghong 2' had lower nitrogen dry matter productivity (NDMP) but higher potassium dry matter productivity (KDMP) than 'Zhenghong 115' .

Low-phosphorus stress substantially increased PDMP and NDMP while decreasing KDMP in both cultivars. Averaging across three silicon levels and two cultivars, compared with P1.0, P0.1 and P0.01 treatments increased PDMP by 274.0% and 363.6%, increased NDMP by 33.2% and 34.1%, and decreased KDMP by 15.4% and 12.2%, respectively, with greater changes in 'Zhenghong 115' than in 'Zhenghong 2'.

Silicon concentration also affected NDMP, PDMP, and KDMP, but the magnitude and trend varied by cultivar and phosphorus level. Compared with Si0, Si1.5 and Si0.75 significantly reduced PDMP of 'Zhenghong 2' under all three phosphorus levels and reduced PDMP of 'Zhenghong 115' under moderate phosphorus deficiency (P0.1). Silicon also reduced NDMP of 'Zhenghong 2' under normal phosphorus (P1.0).

### 2.5 Correlation Analysis of Maize Seedling Growth and Nitrogen, Phosphorus, and Potassium Accumulation

Table 7 shows that, averaging across both cultivars, dry matter accumulation in roots, stem-sheaths, leaves, and whole plants were all highly significantly positively correlated. Dry matter accumulation was highly significantly positively correlated with leaf area and highly significantly negatively correlated with root/shoot ratio. Root morphological indicators were significantly positively correlated with each other and highly significantly positively correlated with dry matter and leaf area. Total nitrogen, phosphorus, and potassium accumulation were highly significantly positively correlated with each other and with dry matter and root indicators. Nitrogen, phosphorus, and potassium accumulation were significantly negatively correlated with their respective root distribution rates. NDMP and PDMP were significantly positively correlated, while PDMP and KDMP were significantly negatively correlated. NDMP and PDMP were significantly negatively correlated with dry matter accumulation, root indicators, and nitrogen, phosphorus, and potassium accumulation, whereas KDMP showed the opposite relationship.

These results indicate that well-developed root systems promote nitrogen, phosphorus, and potassium absorption and dry matter accumulation. The accumulation of nitrogen, phosphorus, and potassium mutually promotes each other, and their synergistic effects enhance root and shoot growth. Root morphology, dry matter, and nitrogen, phosphorus, and potassium accumulation form an interactive network. Combined silicon and phosphorus application improves root morphology, promotes root growth and nutrient accumulation, and thereby influences dry matter accumulation, leaf area, and nutrient productivity to enhance maize growth.

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## Discussion

Roots are crucial absorption and synthesis organs and the first site to sense and transmit nutrient stress signals. Well-developed roots ensure water and nutrient uptake throughout the maize growth period. External nutrient availability directly affects root growth, and plants have adaptive mechanisms under nutrient deficiency, such as altering root morphology, increasing root activity, synthesizing and secreting specific substances, and enhancing metabolic enzyme activities to improve phosphorus absorption and utilization in low-phosphorus environments [13,25-26]. This study confirmed that phosphorus deficiency inhibits maize seedling root growth, reducing total root length, volume, and surface area, decreasing phosphorus absorption and accumulation, and consequently reducing nitrogen and potassium uptake, affecting shoot growth, leaf area, and dry matter accumulation—consistent with previous research. This study also revealed that maize seedlings adapt to varying phosphorus nutrition by altering the distribution of nitrogen, phosphorus, potassium, and dry matter between aboveground and belowground parts. Low-phosphorus stress increases the distribution of these nutrients (especially phosphorus) and dry matter to roots, enhancing absorption capacity.

Genotypic differences exist in low-phosphorus tolerance [25]. Yang et al. [24] identified 'Zhenghong 2' as relatively low-phosphorus tolerant and 'Zhenghong 115'as sensitive through pot experiments. This study found that low-phosphorus stress affected root growth (reductions in length, surface area, and volume) and phosphorus accumulation more severely in 'Zhenghong 115' than in 'Zhenghong 2' , though reductions in nitrogen, potassium, and dry matter accumulation were relatively similar between cultivars—possibly due to different experimental conditions (sand culture with higher phosphorus concentrations). Notably, 'Zhenghong 115' showed much greater increases in phosphorus distribution to roots under low-phosphorus treatment than 'Zhenghong 2', which may represent an important adaptation mechanism.

Silicon plays important roles in plant growth and development, including improving lodging resistance [19], heavy metal cadmium tolerance [27], disease and pest resistance [28], and photosynthetic capacity [29]. Maize is a silicon-accumulating plant that absorbs substantial silicon. Silicon application improves maize photosynthesis [30], increases water use efficiency [29], enhances low-phosphorus tolerance [21], increases nitrogen, phosphorus, and potassium accumulation [16,31], and improves leaf potassium content and yield [17-20]. This study demonstrated that under normal phosphorus conditions, silicon significantly promoted seedling root growth, increasing length, volume, and surface area, enhancing phosphorus absorption and accumulation, and promoting its distribution to leaves. Increased phosphorus accumulation further promoted nitrogen and potassium uptake, enhancing shoot growth, leaf area, and dry matter accumulation, showing clear synergistic effects between silicon and phosphorus. Under moderate phosphorus deficiency, silicon also promoted phosphorus uptake and subsequent nitrogen and potassium absorption and seedling growth, alleviating low-phosphorus stress. However, under severe phosphorus deficiency, silicon showed no significant improvement in nutrient accumulation or dry matter production, indicating that silicon and phosphorus have synergistic rather than substitutive effects, and that combined application should be practiced. Research suggests silicon enhances aerenchyma formation, promotes root oxygen transport, reduces iron and manganese uptake, and improves iron/manganese ratios to enhance phosphorus activity [32], which may represent one mechanism for silicon-promoted phosphorus absorption. However, the mechanisms underlying silicon-phosphorus mutual promotion and synergy require further investigation.

## Conclusion

Phosphorus deficiency inhibits maize seedling root growth, reducing root length, volume, and surface area, decreasing phosphorus absorption and accumulation, and consequently reducing nitrogen and potassium uptake, affecting shoot growth, leaf area, and dry matter accumulation. The impact on roots is less severe than on shoots, resulting in increased root/shoot ratio and enhanced phosphorus distribution to roots and dry matter production efficiency of nitrogen, phosphorus, and potassium—important adaptation mechanisms to low-phosphorus stress. Genotypic differences exist in low-phosphorus sensitivity; between the tested cultivars, 'Zhenghong 115' showed greater reductions in root growth and phosphorus accumulation than 'Zhenghong 2', but adapted by substantially increasing phosphorus distribution to roots.

Silicon application can promote maize seedling growth by increasing root length, volume, surface area, and leaf area, enhancing phosphorus absorption and accumulation, and subsequently increasing nitrogen and potassium uptake and dry matter production, thereby alleviating low-phosphorus stress. However, these effects weaken with decreasing phosphorus concentration, demonstrating clear synergistic and coordinated effects between silicon and phosphorus. Therefore, combined phosphorus and silicon application is recommended in production practice.

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