Journal homepage
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Anbar Journal of Agricultural Sciences
(University of Anbar – College of Agriculture)

PHOSPHORUS AVAILABILITY FROM DIFFERENT FERTILIZERS IN RESPONSE TO SILICON APPLICATION

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Article info

Received: 2024-07-11
Accepted: 2024-09-02
Published: 2025-06-30

DOI-Crossref:
10.32649/ajas.2025.186567

Cite as:
Al-rubaie, J. A. J., and Abdulkareem, M. A. (2025). Phosphorus availability from different fertilizers in response to silicon application. Anbar Journal of Agricultural Sciences, 23(1): 93-106.

Abstract

The effect of silicon (Si) on phosphorus (P) availability in calcareous soil was studied in an incubation experiment carried out at the College of Agriculture, University of Basrah. Treatments were designed according to the following variables: Si levels (0, 100, 200, 300 kg Si ha^{-1}); P levels (0, 12.5, 25, 50 kg P ha^{-1}) and P sources (diammonium phosphate, DAP, and concentrated superphosphate, CSP). Calcium (Ca^{++}) in soil solutions, available P and Si were determined at 7, 14, and 30-day incubation periods. The source of Si was K_2SiO_3. Soluble Ca^{++} declined with increasing Si dosages up to 200 kg Si ha^{-1}, then increased at 300 kg Si ha^{-1}.
On the other hand, available values of P and Si in soil significantly increased with higher Si dosages till 200 kg Si $ha^{-1,}$ then declined at 300 kg Si ha^{-1}. The mean values of available P at 200 kg Si ha^{-1} were 67.05, 160.60, and 79.47 mg kg^{-1} soil for 7, 14, and 30 days of incubation. The effect of P levels, Ca^{++} in soil solutions, available P, and Si increased at higher P levels. Data revealed that soil treated with DAP has larger available P than CSP, while Ca^{++} in soil solution and available Si are unaffected by P source. This suggests that appropriate Si application (100 and 200 kg Si ha^{-1}) could significantly increase P levels in calcareous soils.

Keywords: Available Si, Soluble Ca, DAP, Calcareous soil.

تأثير اضافة السليكون في جاهزية الفسفور من سمادين مختلفين

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الخلاصة

(P) في تربة كلسية. صممت المعاملات وفقًا للمتغيرات التالية: مستويات Si (0، 100، 200، 300 كغم Si هكتار$^{-1}$)؛ مستويات P (0، 12.5، 25، 50 كغم P هكتار$^{-1}$) ومصادر P (فوسفات ثنائي الامونيوم، DAP والسوبر فوسفات المركز، CSP). اما مصدر Si فقد اضيف بشكل سليكات البوتاسيوم (K_2SiO_3). تم تقدير الكالسيوم الذائب (Ca^{+2}) في محلول التربة وP الجاهز وSi الجاهز بعد 7، 14، 30 يومًا من الحضن. انخفض Ca^{+2} الذائب مع زيادة مستويات Si حتى المستوى 200 كغم Si هكتار$^{-1}$، ثم ازداد عند المستوى 300 كغم Si هكتار$^{-1}$. بينما ازداد كل من P وSi الجاهز في التربة بشكل ملحوظ بزيادة مستويات Si حتى المستوى 200 كغم Si هكتار$^{-1}$ ثم انخفضا عند المستوى 300 كغم Si هكتار$^{-1}$. بلغ معدل قيم الفسفور الجاهز عند المستوى 200 كغم Si هكتار$^{-1}$ 67.05، 160.60، 79.47 ملغم كغم$^{-1}$ تربة بعد 7، 14، 30 يومًا من الحضن. اما بالنسبة لمستويات P فقد ازداد Ca^{+2} الذائب وP الجاهز وSi الجاهز بزيادة مستويات P. اظهرت النتائج ان التربة المعاملة بسماد DAP اعطت اعلى قيم للفسفور الجاهز مقارنة بالتربة المعاملة بسماد CSP، بينما لم يتأثر تركيز Ca^{+2} الذائب وكمية Si الجاهز بمصدر P. تشير هذه النتائج الى ان اضافة Si بالمستوى المناسب (100، 200 كغم Si هكتار$^{-1}$) يمكن ان يزيد بشكل كبير من الفسفور الجاهز في التربة الكلسية ويمكن استخدامه كمفتاح لزيادة جاهزية الفسفور الذي يحتاج الى دراسات اضافية في مثل هذه الترب.

كلمات مفتاحية: السليكون الجاهز، الكالسيوم الذائب، فوسفات ثنائي الامونيوم، الترب الكلسية.

Introduction

Phosphorus (P) is a key element controlling plant production. A deficiency of P is considered one of the abiotic stresses limiting crop growth on approximately half of the agricultural soils in the world (18). P is highly immobile in soils and generally is fixed near the application site by precipitation processes with soil, including the formation of surface-adsorbed, complex, dissolution of clay minerals, and slow nucleation, crystallization, and recrystallization of P compounds (28). It is retained in soil by Fe and Al hydroxides, alumino-silicate minerals, carbonates, and organic matter (25). Hence, inorganic P distribution among Ca, Fe, Al, or Si fractions highly depends on soil pH and mineral composition.

At soil pH > 6.5, P is immobilized as Ca-P minerals, whereas at pH < 6.5, P tends to be adsorbed/bound by Fe, Mn, Al, or their hydrous oxides (27). For calcareous soils, P interactions with $CaCO_3$ involve two reactions: adsorption by CaCO surface which occurs at low P concentrations in soil, and the formation of Ca-P crystals. Accordingly, P is one of the elements that have led to large amounts of fertilization to achieve acceptable production levels for farmers. However, intensive and frequent doses of P fertilizers, besides being relatively costly, can create an imbalance in plant nutrients, contribute to soil pollution, and degrade soil properties.

Silicon (Si) fertilization may reduce the demand for P fertilizers in crop soils. Many studies point to the possibility of Si influencing P availability and nutrient use efficiency (1, 10, 17, and 27). Si is released into the soil by the chemical and physical weathering of silica minerals, interaction with other elements to form clay minerals and absorption by plants (8). Various processes confirm the beneficial effects of Si fertilizers in increasing available P in soils. Si is adsorbed onto the low soluble P of Ca, Al, Fe, and Mg by desorption of the P anion (3). Silicic acid competes with P for binding minerals, and increasing Si availability leads to high P mobilization from such minerals (9 and 27). Thermodynamic results show that displacing the P-anion by Si-anion from slightly soluble phosphates and forming corresponding silicates is possible (22), and they suggest the following stages in this process. First, mono-silicic acid concentrations increase along with their adsorption on slightly soluble P of Ca, Mg, Al, and Fe. Next is an exchange of P-anions by Si, followed by desorption of P-anions, leading to an increased P in soil solutions.

A study (27) stated that Si is positively related to P availability and is important for mobilizing P from non-available phases. This could be explained by the decrease in surface-bound Fe-P phases at suitable Si availability, with a slightly lower binding affinity of silicic acid than P. Recently, (16) stated that enhancement of soil microbial activities by adding Si is the key through which Si improves N and P availability. This is based on the hypothesis that the mechanism for Si-driven improvement of soil nutrient availability may be related to microbial action in soil. Similarly, (27) stated that Si positively affects soil respiration in two ways: it increases P availability, enhances soil respiration, and desorbs organic carbon from mineral binding sites (e.g., goethite). With its strong affinity for bonding to minerals compared to C and P, Si may mobilize both elements and directly affect soil respiration.

This study evaluated the effect of a wide range of Si as potassium silicate on the availability of P supplied by two different fertilizers in calcareous soil. The results show the relationship between Si and P availabilities and soluble Ca in soil at different incubation periods.

Materials and Methods

The soil used in the experiment was random clay samples obtained from the Agricultural Research Station, College of Agriculture, University of Basrah, Basrah province, south of Iraq. The samples were air-dried, ground, and sifted using a 2 mm sieve and sorted to determine their basic physiochemical properties and for pre-incubation (Table 1). The soil samples (100 g dry weight) were placed into 150 cm^3 plastic jars and subjected to P and Si fertilization and K for treatment without Si

application to compensate for the K added by silicon fertilizer. The phosphate fertilizers used were triple superphosphate (CSP) with 20.2% P (General Fertilizer Co., Homs, Syria) or diammonium phosphate (DAP) with 21% P (AHG, AAA Holding Group Ltd., IRAQ). The rate of P fertilizers was 0, 12.5, 25, and 50 kg P ha^{-1}. The Si fertilizer tested was potassium silicate with 26.5% SiO_2 (Leaf SIL 21, Frarimpex Co. Ltd., France) added at 0, 100, 200 and 300 kg Si ha-1 rates.

All fertilizer were thoroughly mixed with bulk soil in jars, and the soil samples adjusted to equivalent moisture levels at field capacity. Each treatment was repeated thrice. All jars were incubated at 30˚ C for 30 days. After 7, 14, and 30 days, a set of jars was taken out and analyzed for soluble Ca and available P and Si. Soluble Ca was determined titrimetrically using Na_2 - EDTA and a meroxide indicator in a 1:1 water and soil solution, as described in (26). For available P, soil samples were extracted with 0.5 *M* $NaHCO_3$ (Bray 1), and then P was determined spectrophotometrically using the blue color method described by (23). An available Si was assessed by extracting 2g of soil with 20 ml of 0.01 *M* $CaCl_2$ solution for 16 hrs in a shaker. The extracted solution was treated with acetic acid, ammonium molybdate, tartaric acid, and reduced solution to develop the color, and the readout was recorded at 650 nm wavelength with a spectrophotometer.

Treatment effects on soluble Ca and available P and Si were evaluated using analysis of variance (ANOVA) subjected to three factors (Si levels, P levels, and P sources). Each incubation period was statistically analyzed independently. Statistical analyses were performed using the GenState program, and differences between treatments were assessed using the Least Significant Differences (LSD test) at 0.05 level.

Table 1: Basic physiochemical properties of the used soil.

Properties	Value
PH (1:1) in water	8.08
EC (1:1) (dS m^{-1})	8.5
$CaCO_3$ (g kg^{-1})	302.20
CEC ($Cmol^+$ kg^{-1})	13.98
Available N (mg kg^{-1})	4.20
Available P (mg kg^{-1})	30.4
Available K (mg kg^{-1})	115.16
Organic matter (g kg^{-1})	3.98
Available Si (mg kg^{-1})	22.34
Soluble Ca (mmole L^{-1})	11.1
Texture	Clay

Results and Discussion

The effect of Si and P on soluble Ca in soil: Tables 2 and 5 show the significant effect of Si levels on Ca^{++} concentrations in the soil solution regardless of P levels and sources. Increasing Si dosages from 0 to 200 kg Si ha^{-1} decreased Ca^{++} concentrations, but the levels increased by 300 kg Si ha^{-1}. However, applying Si decreased Ca^{++} concentrations at all levels compared with the control. This was true for all treatments within all incubation periods. Ca^{++} concentration decreased by 27.07, 51.37 and 45.36% with increasing Si from 0 to 200 kg Si ha^{-1} after 7, 14, and 30 days of

incubation, respectively. Table 2 shows the effect of P levels on Ca^{++} concentrations in the soil solution. With higher P levels, Ca^{++} concentrations significantly increased by 30.71, 87.74, and 46.15% at 50 Kg P ha^{-1} compared with the control over 7, 14 and 30 incubation days. Tables 2 and 5 show that the P fertilizer source did not affect Ca^{++} concentration for the three incubation periods.

The interactions among the main factors indicated that the highest values of Ca^{++} concentration were associated with the application of Si at the 200 kg Si ha^{-1} level for all treatments. The higher the Si is applied (300 kg Si ha-1), the less beneficial its effect on Ca^{++} concentration is. In contrast, the highest Ca^{++} concentrations were associated with the highest P level of 50 kg P ha^{-1}. Adding 200 kg Si ha^{-1} and 0 kg P, ha^{-1} resulted in the highest reduction of Ca^{++} concentration in the soil solution, with mean values of 7.53, 1.8, and 4.5 mmole L^{-1} for the 7, 14 and 30 incubation days, respectively. For the effect of P sources, the data in Table 2 indicates the superiority of DAP over CSP when interacting with Si levels after 7 days of incubation.

Table 2: Effect of Si and P levels and P sources on soluble Ca (mmole L^{-1}) in soil solutions for different incubation periods.

Level of Si (kg Si ha^{-1})	CSP×					DAP×				
	0 *	12.5	25	50	Mean	0	12.5	25	50	Mean
After 7 days incubation										
0	11.1	11.31	11.8	13.06	11.82	11.1	13.3	14.95	22.85	15.55
100	10.7	10.4	11.5	12.5	11.27	10.7	14.35	14.43	11.23	12.68
200	7.53	9.9	11.3	12	10.18	7.53	9.56	10.08	9.94	9.28
300	12.2	12.2	12.43	13.75	12.64	12.2	11.06	12.05	13.26	12.14
Mean	10.38	10.95	11.76	12.83		10.38	12.07	12.88	14.32	
After 14 days incubation										
0	4.13	5.45	5.5	5.6	5.17	4.14	5.00	3.66	7.73	5.13
100	1.9	1.7	3.66	4.5	2.94	1.9	1.93	1.7	3.00	2.08
200	1.8	1.9	3.6	3.53	2.71	1.8	1.8	2.8	2.8	2.3
300	2.13	2.9	3.73	5.9	3.66	2.13	2.33	2.8	4.33	2.9
Mean	2.49	2.99	4.12	4.88		2.49	2.76	2.99	4.46	
After 30 days incubation										
0	10.4	11.2	12.05	12.7	11.58	10.4	10.6	11.15	10.7	10.71
100	4.76	7.4	7.6	10.2	7.49	4.76	7.05	7.7	8.2	9.43
200	4.5	4.9	7.55	8.5	6.36	4.5	4.8	5.7	8.3	5.82
300	5.6	8.1	8.2	5.4	6.82	5.6	6.00	6.8	10.1	7.12
Mean	6.31	7.9	8.85	9.2		6.31	7.50	8.34	9.26	

× CSP: Triple superphosphate; DAP: Diammonium phosphate.

* 0, 12.5, 25, and 50 kg P ha^{-1}.

Figure 1 shows the Ca^{++} concentration gradient for the different incubation periods. The higher incubation periods from 7 to 14 days reduced Ca^{++} concentrations though they subsequently increased at 30 days with mean values of 11.94, 3.4 and 7.85 mmole L^{-1}, respectively.

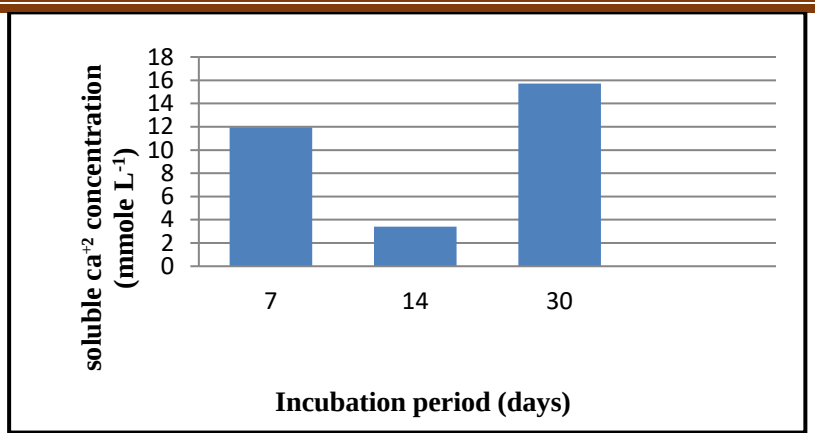

Figure 1: The effect of incubation period on soluble Ca concentrations.

The effect of Si and P on available P in soil: Raising Si levels to 200 kg Si ha^{-1} significantly increased available P in soil, but decreased at 300 kg Si ha^{-1} (Table 3). This was true for all subjected treatments. At an Si application rate of 200 kg Si ha^{-1}, the available amounts of P in soil were 67.01, 160.60, and 79.47 mg kg^{-1} soil for 7, 14 and 30 days of incubation, respectively. However, values at 300 kg Si ha^{-1} were still higher than that for the controls. Table 3 shows a significant increase in available P in soil with increasing P levels. At a P application level of 50 kg P ha^{-1}, the available P was 74.79, 161.91 and 86.25 mg kg^{-1} soil at 7, 14 and 30 days of incubation, with increasing rates of 73.40, 43.41 and 57.04% compared with the counterpart controls, respectively.

The available P in the soil increased significantly with the addition of DAP compared with CSP (Table 3) at increasing rates of 7.49, 7.84 and 7.78% at 7, 14 and 30 days incubation, respectively. The addition of Si at 200 kg Si ha^{-1} (or 100 kg Si ha^{-1}) along with 50 kg P ha^{-1} gave the highest values for available P at 81.08, 177.90 and 91.29 mg kg^{-1} soil for 7, 14 and 30 days incubation, respectively. Further addition of Si decreased the values at all P levels.

For incubation period, the available P of soil incubated for 7 days was 62.17 mg kg^{-1} soil, increasing to 139.07 mg kg^{-1} soil after 14 days and decreasing to 72.93 mg kg^{-1} soil after 30 days (Fig. 2).

Table 3: Effect of Si and P levels and P sources on available P (mg kg^{-1} soil) in soil for different incubation periods.

Level of Si (kg Si ha^{-1})	CSP×					DAP×				
	0 *	12.5	25	50	Mean	0	12.5	25	50	Mean
After 7 days incubation										
0	30.85	53.82	61.87	65.30	52.96	30.85	61.10	64.74	77.68	58.59
100	55.45	63.11	66.47	79.98	66.25	55.45	67.52	70.02	82.18	68.79
200	46.06	64.68	70.13	72.07	63.23	46.06	73.55	82.42	81.18	70.80
300	40.15	57.16	64.71	67.11	57.28	40.15	60.78	64.13	72.85	59.48
Mean	43.13	59.69	65.79	71.12		43.13	65.74	70.33	78.47	
After 14 days incubation										
0	47.50	101.21	120.10	138.50	101.80	47.50	109.20	116.61	161.62	108.71
100	131.70	137.70	144.60	149.81	141.00	131.70	147.90	155.42	174.20	152.30
200	137.60	153.80	159.21	168.11	154.70	137.60	166.81	173.82	187.71	166.51
300	134.80	126.70	146.71	142.51	137.71	134.80	136.81	155.11	172.81	149.91
Mean	112.90	129.90	142.71	149.71		112.90	140.10	150.20	174.11	
After 30 days incubation										
0	37.18	68.66	71.91	72.84	62.65	37.18	73.31	80.29	95.82	71.65
100	67.11	78.42	84.47	83.70	78.42	67.11	77.21	82.61	98.89	81.43
200	66.49	71.14	85.00	83.08	76.43	66.49	80.05	85.09	98.43	82.52
300	48.89	64.47	68.04	72.02	63.37	48.89	64.47	70.05	85.17	67.15
Mean	54.92	70.67	77.36	77.92		54.92	73.76	79.51	94.58	

× CSP: Triple superphosphate; DAP: Diammonium phosphate.

* 0, 12.5, 25, and 50 kg P ha^{-1}.

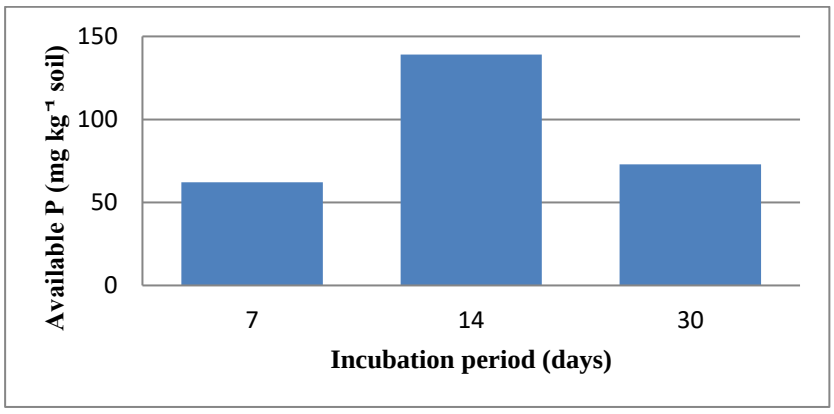

Figure 2: The effect of incubation period on available P.

The effect of Si and P on available Si in soil: The effect of Si and P on available Si in soil is shown in Table 4. Increasing Si levels significantly increased the amount of available Si up to 200 kg Si ha^{-1}, then declined at 300 kg Si ha^{-1} though still above the control (no Si addition). This result was similar for all incubation periods. The averages for 0, 100, 200, 300 kg Si ha^{-1} were 32.97, 53.74, 56.89 and 43.14 mg kg^{-1} soil at 7 days, 48.60, 62.21, 67.65 and 60.80 mg kg^{-1} soil at 14 days, and 1.74, 2.19, 2.83 and 1.80 mg kg^{-1} soil at 30 days, respectively. There was a positive correlation between higher P and Si availability in the soil. The higher rates for increasing P levels from 0 to 50 kg P ha^{-1} were 37.44 and 30.35% at 7 and 14 days of incubation, respectively. While the significant differences at 30 days were not clear, higher values were obtained at 25 kg P ha^{-1}.

The results showed no significant effect of P sources (CSP and DAP) on Si availability at the three incubation periods (Table 5). Further, no significant differences occurred in available Si from the interaction effect of the main factors in the experiment, except those between Si and P levels at 14 days incubation. This indicates that increasing Si levels up to 200 kg Si ha^{-1} raised available Si but declined at 300 kg Si ha^{-1} for all P levels. In line with that trend, higher P levels raised available Si for all Si levels.

The available Si in soil at different incubation periods is shown in Figure 3. The available Si peaked at 59.81 mg kg^{-1} soil at 14 days, then decreased sharply to 2.14 mg kg^{-1} soil at day 30. These results are similar to those on available P in soil (Fig. 2).

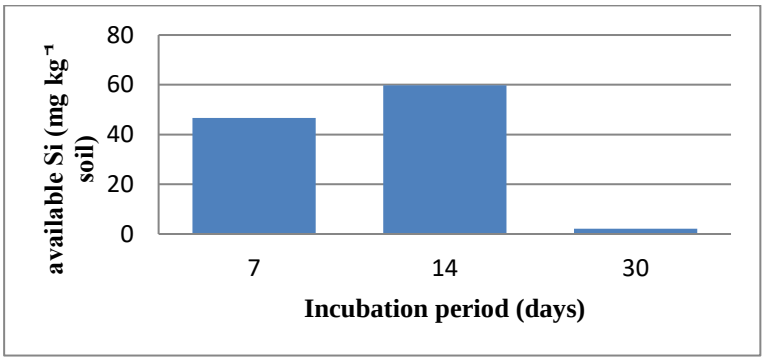

Figure 3: The effect of incubation period on available Si.

Table 4: Effect of Si and P levels and P sources on available Si (mg kg^{-1} soil) in soil for different incubation periods.

Levels of Si (kg Si ha^{-1})	CSP×					DAP×				
	0 *	12.5	25	50	Mean	0	12.5	25	50	Mean
After 7 days incubation										
0	22.34	27.60	33.18	46.59	32.43	22.34	30.00	37.96	43.74	33.51
100	48.19	51.11	57.88	55.89	53.27	48.19	54.03	55.89	58.75	54.21
200	51.11	60.67	57.88	60.67	57.58	51.11	56.49	56.56	60.67	56.21
300	35.17	35.69	40.15	52.68	40.92	35.17	46.99	47.26	52.02	45.36
Mean	39.20	43.77	47.27	53.96		39.20	46.88	49.42	53.80	
After 14 days incubation										
0	28.50	44.10	56.50	68.80	49.50	28.50	51.70	55.70	57.91	47.71
100	59.80	66.80	68.41	63.91	64.71	59.80	58.71	58.50	61.90	59.71
200	65.30	66.00	64.00	88.31	70.90	65.30	61.20	61.11	69.80	64.40
300	53.80	56.80	61.60	64.20	59.10	53.80	68.40	58.00	69.61	62.51
Mean	51.90	58.40	62.61	71.30		51.90	60.00	58.30	64.01	
After 30 days incubation										
0	1.94	1.29	2.03	1.72	1.74	1.94	1.45	2.65	0.98	1.75
100	2.26	1.80	2.80	1.82	2.17	2.26	1.57	2.82	2.19	2.21
200	3.29	2.92	2.99	2.95	3.04	3.29	1.73	2.93	2.57	2.63
300	2.26	0.85	2.61	1.94	1.80	2.26	1.07	1.88	2.00	1.80
Mean	2.43	1.71	2.49	2.11		2.43	1.45	2.57	1.93	

× CSP: Triple superphosphate; DAP: Diammonium phosphate.

*** 0, 12.5, 25, and 50 kg P ha^{-1}.**

Table 5: LSD values (at 0.05 level) of soluble Ca, available P and available Si under experimental variables.

S.O.V	7 Days			14 Days			30 Days		
	Soluble Ca	Available P	Available Si	Soluble Ca	Available P	Available Si	Soluble Ca	Available P	Available Si
Si level (Si)	0.74	3.25	4.14	0.70	7.60	5.73	0.67	5.04	0.54
P level (P)	0.74	3.25	4.14	0.70	7.60	5.73	0.67	5.04	0.54
P source (f)	NS	2.30	NS	NS	5.38	NS	NS	3.56	NS
Si×P	1.49	6.51	NS	NS	15.21	11.46	1.34	10.08	NS
Si×f	1.05	NS	NS	NS	NS	NS	NS	NS	NS
P×f	NS	NS	NS	NS	10.75	NS	NS	7.13	NS
Si×P×f	2.11	NS	NS	NS	NS	NS	1.9	NS	NS

NS: non-significant.

As an important element, optimum amounts of Si nutrients can enhance P availability in soil by various means. This is more obvious in low P soils such as calcareous soils as the ability of Si to compete with P is highly pH-dependent since the Pka value of silicic acid is higher than that of H_3PO_4 (14). In such soils, Ca^{++} interacts with the mechanism by releasing P from complexes of Ca-P. Appropriate Si applications decreased Ca^{++} concentrations in soil solutions, while excessive applications increased them. At Si level 200 kg Si ha^{-1}, Ca^{++} reached its minimum value for all treatments under study. The application of Si to soil seemed to create a formation of Ca-Si complexes resulting in a reduction of Ca^{++} concentrations in soil solutions (5). (13) reported a high affinity of Si to bond with metals in solution and then be adsorbed onto clay particles. (19) also suggested that Si minerals have basic specifications allowing them to attract cations to their surfaces. Increasing Ca^{++} concentrations in soil solutions at higher levels of Si (300 kg Si ha^{-1}) may be attributed to the bonding of P with the Si surface. This increases with higher application levels and a part of it may be converted to high surface area forms such as polysilicic acid and amorphous silicic acid, that free Ca^{++} in soil solutions (21). This conclusion is supported by the decrease in available P and Si at this level (Tables 3 and 4). Further, high Si enrichment (applied as K_2SiO_4) increases K concentrations in soil solutions which was able to replace Ca^{++} on clays surface resulting in increased Ca^{+} concentrations in soil solutions (7).

Increasing P levels significantly increased Ca^{++} concentration in soil solutions (Table 2) due to the high content of Ca in CSP fertilizer (about 12 - 14%) as reported by (25). However, for DAP fertilizer, the neutral pH in the saturated solution of this fertilizer may reduce the probability of dissolution of salts and compounds in soil resulting in free concentrations of Ca^{++} in soil solution. Similar results were obtained by (2). Although the effect of P sources on Ca^{++} concentrations is insignificant, the interaction of P source with Si levels clearly indicates higher values of Ca^{++} associated with DAP compared with CSP. This may illustrate that DAP can effectively reduce Ca compounds/complexes due to it neutral reaction resulting in a reduction of dissolution of salts. This result is supported by the increasing availability of P at DAP compared with CSP (Table 3). Figure 1 shows that decreasing Ca^{++} concentrations at 14- and 30-

day durations compared with 7 days may be attributed to Ca adsorption on soil colloids after 14 days incubation to achieve an equilibrium state between the soil solutions and the surfaces of soil particles (11).

Table 3 shows that appropriate levels of Si seemed to create competition between Si and P for sorption sites resulting in an increase in available P in the soil. The beneficial effect of Si on enhancing available P was confirmed through several ways. The application of Si leads to its adsorption onto the slightly soluble P of Ca, Mg, Fe and Al by desorption of the P anion (3). Silicic acid competes with P for binding minerals increasing Si availability and leading to the high mobilization of P from such minerals (9 and 27). Recently, the enhancement of microbial activities after addition of Si sources resulted in an increase of P availability in soil (16). Similar results were obtained by (1, 10 and 17).

Increasing Si enrichment to 300 kg Si ha^{-1} significantly decreased available P to about 12.87, 10.45 and 17.88% for the 7, 14 and 30-day incubation periods, respectively compared with 200 kg Si ha^{-1}. However, the available P values at 300 kg Si ha^{-1} were still higher than that of control. Similar results were recorded by (16 and 17). In this study, the decrease in available P may be attributed to the increase in Ca^{++} concentrations in the soil solution at 300 kg Si ha^{-1} (Table 2) resulting in slight available amounts binding with P. Further, (24) stated that the application of silicate ions to soil with pH ranged between 4-9 converts to amorphous silicic acid (H_3SiO_4). This may be produced at high levels of Si, has a lower negative surface charge compared to the P anion, and therefore should not replace P on binding sites of soil and/or preferentially absorbed when both are in the soil solution. In contrast, many previous studies (14 and 29) found that only high Si levels were able to enhance P desorption.

The available P significantly increased with the amount of P. The higher the P levels, the higher the available P in the soil, as noted by (15). Higher available P in soil was obtained using DAP compared with CSP (Table 3) with mean values of 94.82 and 87.98 mg kg^{-1} soil, respectively. Similar results were obtained by (12 and 20) who confirmed that DAP fertilizer does not introduce more precipitated materials in soil due to it neutral pH. The amount of available P increased with higher incubation periods from 7 and 14 days then declined at the end of the experiment (30 days) (Fig. 2) indicating a reverse trend to that of soluble Ca^{++} (Fig. 1). It might be possible that increasing Ca^{++} in soil solutions will increase the prospects for reactions with available P making Ca-P complexes.

Increasing Si levels from 0 to 200 kg Si ha^{-1} significantly increased Si availability in soil (Table 4). However, further increasing it to 300 kg Si ha^{-1} led to decreased available Si, as occurred for available P (Table 3), meaning that the two elements trend similarly in respect to Si application. That was also true in respect to P levels and P sources as well as incubation times. Similar results were reported by (1 and 4). The reduction in available Si at 300 kg Si ha^{-1} may be attributed to increasing Ca^{++} concentrations in soil solutions (Table 2) and forming Ca-Si complexes (5) resulting in a less available Si. Furthermore, (21) stated that high concentrations of monosilicic acid can combine with heavy metals (Cd, Pb, Zn, Hg and others) in poorly soluble metal silicates.

Analysis of Table 4 showed that increasing P dosages leads to higher availability of Si in soils. The supply of P might enhance P adsorption on silicate materials forming soluble compounds (6) rather than the interaction of Si with Ca which increased with higher P dosages. Such a reaction depends on Si sources and applied P levels. (21) found that Si-rich materials can adsorb P forming plant-available forms, and these materials varied in their capacity to adsorb P from soil solutions. For example, they found that $CaSiO_3$ adsorbed P from wide levels of P. In regard to the effect of incubation time on Si availability, Figure 3 illustrates that the context of Si and P variations are similar but opposite with Ca^{++} in soil solutions. This confirms the idea that Si can enhance the availability of P in soils and, in return, P readily preserves Si.

Conclusions

The proper dosage (200 kg Si ha^{-1}) of Si as K_2SiO_3 can increase available amounts of P in soil due to decreasing Ca^{++} concentrations in soil solutions. Further, a dosage of 300 kg Si ha^{-1} decreases available P after increasing Ca^{++} concentration. In return, P dosages enhance Si availability. Soil treated with DAP offered higher values of available P compared with CSP. However, the source of P fertilizer cannot affect available Si and soluble Ca^{++}. In conclusion, K_2SiO_3 as a source of Si has a crucial role in enhancing available P in P-deficient calcareous soils.

Supplementary Materials:

No Supplementary Materials.

Author Contributions:

Author 1; methodology, writing—original draft preparation, Author 1 and Author 2 writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding:

This research received no external funding.

Institutional Review Board Statement:

The study was conducted in accordance with the protocol authorized by the Department of Soil Sciences and Water Resources, College of Agriculture, University of Basrah.

Informed Consent Statement:

No Informed Consent Statement.

Data Availability Statement:

No Data Availability Statement.

Conflicts of Interest:

The authors declare no conflict of interest.

Acknowledgments:

Non.

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