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Effect of Silicon and Phosphorus Additions and Their Interactions on Wheat Plants Grown on a Clay Soil

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A pot experiment was conducted in clay soil collected from Agricultural Research Center farm, Giza governorate, Egypt. Wheat grains (*Triticum aestivum* L., Giza 168) were cultivated to study the effect of silicate and phosphate ions as well as their interactions on the growth and nutritional status of the growing plants, beside their availability in the studied soil. Silicon (Si) in the form of sodium meta-silicate penta-hydrate ($Na_2SiO_3.5H_2O$) was added at a rate of 0, 200, 300 and 400 mg Si kg^{-1} soil, and phosphorus (P) in the form of calcium super phosphate was given at a rate of 0, 3.5, 7.0, 10.0 and 13.0 mg P kg^{-1} soil to represent 0, 25, 50, 75 and 100% of the recommended rate of P fertilization by the Egyptian Ministry of Agriculture for wheat cultivation. Also, the experiment included combinations between all these concentrations of Si and P. Obtained results showed that Si and P availability increased in the studied soil with increasing either Si or P concentrations added. This means that P availability in soil as an essential element for plant growth can be

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improved by addition of Si. Also, Si increased in plant with increasing applied Si concentrations. Interaction between Si and P generally increased all parameters of plant growth; such responses were significant for fresh and dry weights of wheat plants at booting stage. It could be recommended that selecting good P fertilization design, including time and rate of addition, goes along with values of available Si in the soil.

Keywords: Silicon; phosphorus; interactions; wheat plant; clay soil.

1. INTRODUCTION

Silicon (Si) is a basic mineral formatting element, which is considered the second most abundant element in the earth's crusts [1]. It is known as non-essential element for higher plants, while lately it confirmed its role in enhancing crop yield by promoting several desirable plant physiological processes. Silicon fertilization has been reported to result in increased soil exchange capacity, improved soil aggregation; consequently improved water and air regimes, transformation of P-containing minerals and formation of alumino-silicates and heavy metal silicates [2]. The amount of literature documenting the benefits of Si on plants is vast and primarily highlights the value of Si fertilization in maintaining plant productivity under stressed conditions [3,4]. The established Si-induced mechanisms to improve plants' resistance to biotic and abiotic stresses take place in the soil, the root system, and inside the plant. Silicon deposition as silica in shoots and leaf epidermis, also known as the mechanical barrier hypothesis [5], enhances the plant's mechanical strength and protective layer. This barrier is believed to help promote the plant's resistance to pathogens, improve plants' tolerance to abiotic stresses and increase photosynthetic rates [6,7].

Phosphorus (P) is a macro-nutrient that has the most influence on plants growth and productivity, and according to statistics of Egyptian Ministry of Agriculture more than 50% of the cultivated areas are in P-deficient soils [8]. The low availability of P in those soils is one of the greatest challenges in the fertilization of those soils. There are various factors that interfere with the availability of P in the soil, including the environmental factors that control the activity of microorganisms which immobilize or liberate the orthophosphate ions, the physiochemical and mineralogical properties of the soil [9], and the silicon-phosphorus interactions [10,11]. One of the most effective solutions to raise the P availability is to exploit the relationship between it and Si concentration in the soil. Ma and Takahashi [12] studied the effect of Si on the growth and P uptake of rice and found that, addition of Si raised the optimum P level for rice and enhanced plant growth and yield. Alovisi et al. [13] studied the Si-P interactions in some soils cultivated with bean plants in Brazil and found that, application of silicate could increase P availability to plants, based on the fact that the silicate anion occupies the adsorption sites of the phosphate anion, which reflect on enhancing plant growth and yield and increasing the content of its different parts with P. Greger et al. [14] reported that Si increased the availability of P; it might be due to that Si modifies uptake and acquisition of P for plants. Silicon is known to reduce the soil sorption of P, especially at low pH, thus, increases the plant-available portion of P in the soil [15].

Wheat (*Triticum aestivum* L.) is the most important cereal crop in Egypt where it provides more than 30% of the population's calorie intake [8]. Works related to the use of Si to enhance P fertilization efficiency and uptake in wheat plant are rare in Egypt to date. Thus, the main objective of this investigation is to study the effect of silicate and phosphate ions as well as their interactions on the nutritional status of growing wheat plants, beside their availability in the studied clay soil.

2. MATERIALS AND METHODS

A pot experiment was conducted in clay soil classified as *Entisol*, collected from Agricultural Research Center farm, Giza governorate, Egypt (29^{o} $58^{/}$ $55.046^{//}$ N and 31^{o} $12^{/}$ $49.272^{//}$ E). Soil samples (0-30 cm) were air-dried, crushed and finely ground, then sieved to pass through a 2 mm sieve. Some physical and chemical characteristics of the studied soil samples were achieved as described by [16,17] and the results are presented in Table 1. The study was conducted by growing wheat grains (*Triticum aestivum* L., Giza 168) under open field conditions. Twenty grains were sown per pot (15.5 cm inter-diameter and 21 cm height, containing 4 holes); each pot had 5 kg of the studied soil samples after preparation.

Phosphorus treatments were performed using calcium super phosphate (15% P_2O_5) supplied at a rate of 0, 3.5, 7.0, 10.0 and 13.0 mg P kg^{-1} soil to represent 0, 25, 50, 75 and 100% of the recommended rate of P fertilization by the Egyptian Ministry of Agriculture for wheat cultivation. It was added before one week of plant cultivation and mixed uniformly with the studied soil in pots. Silicon in the form of sodium meta-silicate penta-hydrate ($Na_2SiO_3.5H_2O$, 13% Si) was added at a rate of 200, 300 and 400 mg Si kg^{-1} soil, in addition to the control treatment (without any Si additions). Silicon concentrations were applied to the soil once, after sowing the grains of wheat plants. Also, the experiment included combinations between all these concentrations of Si and P. The experimental design was laid out in a split plot one with three replications. The main plots were assigned to the P additions and the subplots were occupied by the Si applications.

Nitrogen was added in the form of ammonium nitrate (33.5% N) at a rate of 100 kg N fed^{-1} for wheat cultivation. It was added in three spilt of equal doses after 2, 4 and 7 weeks from sowing. Potassium was added in the form of potassium sulfate (48% K_2O) at a rate of 50 kg K_2O fed^{-1} for wheat plants. It was added once after 4 weeks from cultivation. The moisture content in the studied soil was maintained at field capacity using tap water (EC_W 0.07 dS m^{-1}) till the end of the experiment.

Plants were harvested at booting growth stage (60 days from sowing), divided into root and shoot, and weighted the fresh and dry weights. Plant samples representing each studied treatment were oven dried at 70^oC for 48 h, then ground in a stainless mill to be finally digested using a mixture of sulfuric acid and hydrogen peroxide according to the method described by [18]. Aliquots were finally taken out and analyzed for total Si and P using Spectrophotometer [17].

After plant harvest, soil samples were subjected to analyses of the studied elements to determine their availability. The available Si was extracted by 0.5 M acetic acid as described by [19] and determined colorimetrically as yellow silico-molybdic acid according to [17]. Available P was extracted by using sodium bicarbonate ($NaHCO_3$) 0.5 M at pH 8.5 according to [20] and determined using Spectrophotometer by using ascorbic acid method.

The obtained data of soil and plant were statistically analyzed according to the method described by [21] using the LSD at 5% level of significance. Coefficient of determination (R^2) was calculated between available Si and P in soil and their contents in plant using linear equation.

3. RESULTS AND DISCUSSION

3.1 Availability of Silicon and Phosphorus in Soil

Data presented in Table 2 shows the available concentrations of Si and P in the studied clay soil at booting growth stage of wheat plants as affected by their ground application. Results revealed that available Si increased with increasing its applied dose in soil, with significant increases (at 5% level of significance) as compared to the control treatment. The highest increase (56%) occurred due to application of 400 mg Si kg^{-1}, as compared to control. This result agreed with those of [22] who found that available Si in soil significantly increased with increasing the rate of silicate application and consequently affected the absorbed Si by plants. Also, the available P increased with increasing its applied concentration in soil, with significant differences as compared to the control treatment. The application of 3.5 mg P kg^{-1} soil gave the lowest increase (34%) in available P, while the highest increase (50%) was given by the treatment having 13 mg P kg^{-1} soil as compared to control. These findings agreed with those obtained by [23] who reported that soil available P was positively and significantly affected by increasing P application in the soil.

Regarding the interaction between the applied Si and P concentrations in soil, data illustrated in Fig. 1 showed that, Si application increased the Si availability in soil under conditions of various P concentrations (Fig. 1A), as compared to the control treatment. Phosphorus application increased the P availability in soil under various Si concentrations (Fig. 1B), as compared to control. Phosphorus availability increased with increasing the concentration of either Si or P (Fig. 1C), as compared to control. Silicon availability increased with increasing either P or Si (Fig. 1D), as compared to control. Ma and Takahashi [12] reported that Si can improve soil P bioavailability through sorptive interaction between the two elements and enhancement of phosphate solubility.

3.2 Vegetative Growth Parameters of Wheat Plants as Affected by Si and P Additions and Their Interactions

Data in Table 3 shows the effect of either Si or P on fresh and dry weights along with moisture content in shoots and roots of wheat plants at booting growth stage. Results showed that application of 400 mg Si kg^{-1} soil gave the highest increase percent for fresh and dry weights of either shoots (38.1 and 48.4%, respectively) or roots of wheat plants (24.7 and 54.5%, respectively), as compared to the control treatment. These findings agreed with those obtained by [24] who reported that shoot and root dry weights of wheat plants increased with Si applied. In that sense, [25] stated that Si played a favorable role in plant growth, mineral nutrition, and mechanical strength. The increase in plant growth may be attributed to the changes in physiological and morphological properties which are facilitated by the presence of Si. On the contrary, the treatment of 400 mg Si kg^{-1} soil gave the lowest value of moisture content in shoots and roots of wheat plants at booting growth stage (after 60 days from cultivation), and this confirmed increasing the dry matter content by applying this treatment. Regarding the effect of P, results in Table 3 showed that, the treatment of 13 mg P kg^{-1} soil gave the highest % increase in the fresh and dry weights of shoots (31 and 67%, respectively) or roots of wheat plants (78 and 154%, respectively), as compared to control. These results agreed with those obtained by [26] who reported that dry weight of shoots and roots of wheat plants increased substantially as the P application rate increased. Increasing the P application rate to the soil greatly increased root dry weight, root length and density, and consequently root surface area of the cultivated plants. Additionally, [27] stated that the increment in growth and yield due to P fertilization may be attributed to the activation of metabolic processes, where its role in building phospholipids and nucleic acid is known. Moreover, this treatment (13 mg P kg^{-1} soil) gave the lowest value of moisture content in shoots and roots of wheat plants.

Data in Table 4 shows that the interaction between Si and P applications, generally, increased the growth parameters of wheat plants. This may be due to some sort of synergetic interaction between them [3]. Also, the treatment of 400 mg Si kg^{-1} in combination with 13 mg P kg^{-1} soil gave the highest % increase in fresh and dry weights of shoots (50 and 62%, respectively) and roots of wheat plants (109 and 186%, respectively), as compared to the control treatment. Regarding the moisture content in shoots and roots of wheat plants at booting growth stage, there are either no significant differences among the studied treatments as compared to the control treatment or the control treatment has the highest values. In this same light, [28] reported that Si promoted the growth of maize seedling, dry matter accumulation of different organs and root/ shoot ratio under low P stress. Also, [15] found that application of silicate and phosphate increased the shoot and root dry weights of maize plants and the greatest increases were observed when silicate was applied together with phosphate.

3.3 Silicon and Phosphorus Concentrations in Wheat Plants at Booting Growth Stage

Data in Table 5 shows that Si concentration and its total content in shoots and roots of wheat plants at booting growth stage were increased by increasing its applied concentrations in the studied soil. This response was clearer with roots than shoots. Also, data illustrated in Fig. 2 (A and B) showed strong relations between the available Si in soil and its concentration in both shoots and roots (R^2= 0.93 and 0.99) of wheat plants, respectively. These results were in coincidence with those obtained by [29] who reported that there was a significant direct relationship between tissue (shoot and root) Si content and its applied rate in the soil. While, [24,30] added that plant supplied with exogenous Si had high concentration of Si in shoot. Also, the accumulation of Si in shoots and roots of wheat plants increased with increasing the applied rate as compared to the control treatment. Regarding the P concentration and its total content in shoots and roots of wheat plants, data in Table 5 showed that, there were significant increases in plant organs with P which related positively with its applied concentration in the studied soil. Data illustrated in Fig. 3 (A and B) confirmed these results, which show the relation between available P in soil and its concentration in shoots of grown wheat plants was equal 0.83 and in roots = 0.85. These results were in concordance with those obtained by [26] who reported that the concentration of P in different plant organs increased with increasing its applied rate in the soil.

Table 1. Some physical and chemical characteristics of the studied soil

Particle size distribution (%)		**Soluble ions** (meq L^{-1})	
C. Sand	6.22	Ca^{2+}	4.18
F. Sand	2.66	Mg^{2+}	2.98
Silt	26.1	Na^{+}	2.75
Clay	65.0	K^{+}	1.91
Textural class	Clay	HCO_3^-	5.61
FC (%)	42.8	Cl^-	2.29
WP (%)	4.12	SO_4^{2-}	3.92
AW (%)	38.7	Available elements (mg kg^{-1})	
OM (%)	0.96	N	55.2
$CaCO_3$ (%)	3.33	P	23.0
pH (1: 2.5 soil: water suspension)	7.80	K	189
EC (dS m^{-1}, in paste extract)	1.12	Si	300

Carbonate ions were not detected.

C. Sand means coarse sand, F. Sand means fine sand, FC means field capacity, WP means wilting point, AW means available water and OM means organic matter

Table 2. Available Si and P in the studied soil at booting growth stage of wheat plants as affected by their ground applications

Treatment mg Si kg^{-1}	**Available Si mg Si kg^{-1}**	**Treatment mg P kg^{-1}**	**Available P mg P kg^{-1}**
0.00	300	0.00	23.0
200	438	3.50	30.8
300	450	7.00	31.9
400	468	10.0	33.6
		13.0	34.4
$LSD_{0.05}$	13.4	$LSD_{0.05}$	5.90

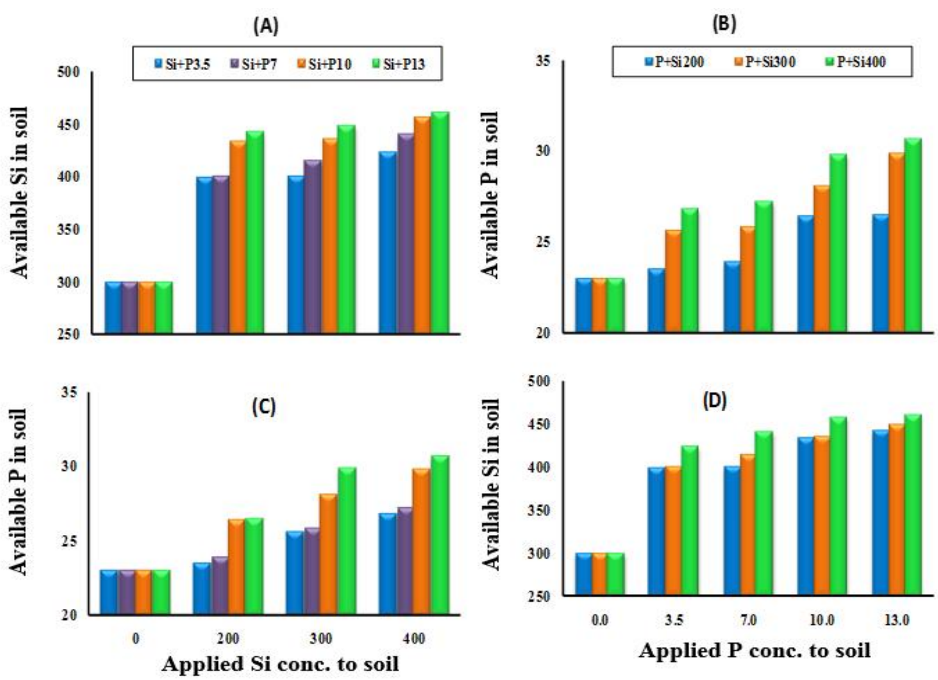

Fig. 1. Available concentration (mg kg^{-1}) of Si and P as affected by their interactions in the studied soil at booting growth stage of wheat plants

Table 3. Fresh and dry weights of shoots and roots of wheat plants at booting growth stage as affected by Si and P applications to the studied soil

Treatment mg kg^{-1}	Fresh weight g plant^{-1}		Dry weight g plant^{-1}		Moisture content %	
	Shoots	Roots	Shoots	Roots	Shoots	Roots
Control	6.99	0.85	1.26	0.22	82.0	74.0
			Si Concentrations			
Si_{200}	7.25	0.88	1.36	0.25	81.0	72.0
Si_{300}	8.28	0.95	1.50	0.27	82.0	72.0
Si_{400}	9.65	1.06	1.87	0.34	81.0	68.0
$LSD_{0.05}$	0.55	0.16	0.33	0.02	3.08	4.05
			P Concentrations			
$P_{3.5}$	8.47	1.17	1.77	0.23	79.0	80.0
$P_{7.0}$	8.61	1.23	1.81	0.29	79.0	76.0
$P_{10.0}$	9.00	1.33	2.01	0.32	78.0	70.0
$P_{13.0}$	9.18	1.52	2.11	0.56	77.0	63.0
$LSD_{0.05}$	0.90	0.22	0.30	0.06	4.81	5.35

Table 4. Effect of Si and P interactions on fresh and dry weights of shoots and roots of wheat plants at booting growth stage as affected by their applications to the studied soil

Treatment mg kg^{-1}		Fresh weight g plant^{-1}		Dry weight g plant^{-1}		Moisture content %	
		Shoots	Roots	Shoots	Roots	Shoots	Roots
$P_0 \times Si_0$		6.99	0.85	1.26	0.22	82.0	74.0
$P_{3.5}$	Si_{200}	7.80	0.91	1.26	0.26	82.2	71.3
	Si_{300}	7.87	1.07	1.48	0.31	80.8	71.4
	Si_{400}	8.41	1.25	1.67	0.36	80.2	71.4
$P_{7.0}$	Si_{200}	7.78	1.08	1.49	0.31	80.8	71.1
	Si_{300}	8.12	1.24	1.55	0.34	80.9	72.9
	Si_{400}	9.77	1.48	1.82	0.45	81.4	69.5
$P_{10.0}$	Si_{200}	8.43	1.21	1.67	0.37	79.8	69.3
	Si_{300}	8.83	1.38	1.76	0.39	80.0	71.6
	Si_{400}	10.0	1.51	1.97	0.49	80.4	67.3
$P_{13.0}$	Si_{200}	8.66	1.37	1.87	0.39	78.4	71.6
	Si_{300}	9.71	1.47	1.94	0.41	80.0	72.3
	Si_{400}	10.5	1.78	2.04	0.63	80.6	64.7
$LSD_{0.05}$		0.96	0.11	0.14	0.05	2.77	3.69

Table 5. Concentration and total content of Si and P in shoots and roots of wheat plants at booting growth stage as affected by their applications to the studied soil

Treatment mg kg^{-1}	Concentration mg g^{-1}		Total content mg plant^{-1}	
	Shoots	Roots	Shoots	Roots
		Si Concentrations		
Si_0	3.50	4.60	4.41	1.01
Si_{200}	5.72	6.73	7.78	1.68
Si_{300}	6.35	6.93	10.9	1.87
Si_{400}	7.30	7.07	11.9	2.40
$LSD_{0.05}$	0.97	0.40	1.50	0.37
		P Concentrations		
P_0	4.05	3.90	5.10	0.86
$P_{3.5}$	5.80	4.40	10.3	1.01
$P_{7.0}$	6.00	4.70	10.9	1.36
$P_{10.0}$	6.80	4.90	13.7	1.57
$P_{13.0}$	7.50	5.30	15.8	2.97
$LSD_{0.05}$	0.66	0.60	2.30	0.27

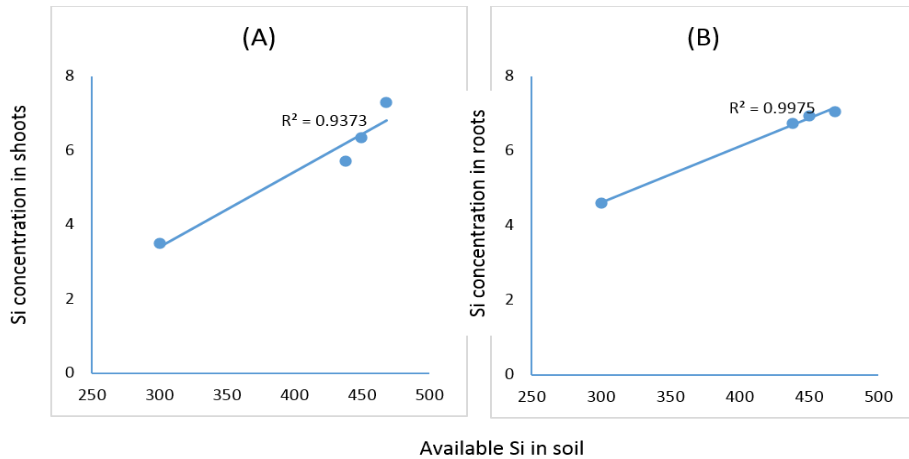

Fig. 2. The relationship between available Si concentration (mg kg^{-1}) in the studied soil and its concentration (mg g^{-1}) in shoots and roots of the growing wheat plants

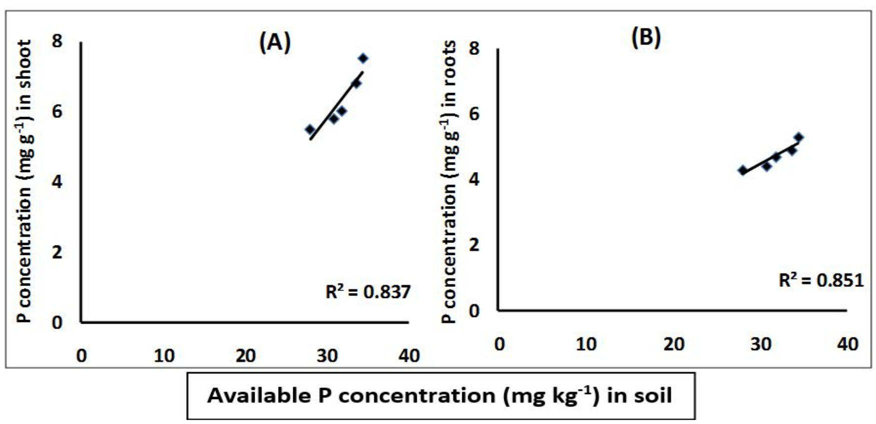

Fig. 3. The relationship between available P concentration in the studied soil and its concentration in shoots and roots of the growing wheat plants

Data in Table 6 shows the effect of the interaction between Si and P on concentration and total content of Si in shoots and roots of wheat plants at booting growth stage. Results showed that the treatment of 400 mg Si kg^{-1} in combination with 13 mg P kg^{-1} soil gave the highest concentration and total content of Si in shoots and roots of wheat plants. Similar results were found with P concentration and total content per plant as affected by the same interaction in the soil (Table 7). Data in Table 8 showed positive and, in general, strong relation between available concentration of Si and P in the soil, and their concentrations in shoots and roots of the grown wheat plants. These data agreed with those obtained by [31] who found that Si application tended to increase P content in the green tops. These data suggested that Si enhanced P mobilization from metabolically less active to metabolically more active tissue. In addition, [24] found that Si application markedly increased the concentration of P in shoots. The increase in Si concentration in root medium may increase the uptake of P. It may be due to desorption of P from adsorption sites within the soil. Bai et al. [32] reported that the critical levels of soil Olsen-P for optimal crop yield ranged from 10.9 to 21.4 mg kg^{-1}, and these levels were highly affected by crop species, soil type, soil pH and soil organic matter content. While the critical levels of soil available Si extracted by 0.5 M acetic acid for rice plants ranged from 44 to 116 ppm, according to [33]. Considering these levels into account, the applied P in the studied soil till 13 mg kg^{-1} considered adequate, while applying Si to the studied soil till 400 mg kg^{-1}considered high but not within the toxic range according to the previous studies of [13].

Table 6. Concentration and total content of Si in shoots and roots of wheat plants at booting growth stage as affected by Si and P interactions in the studied soil

Treatment mg kg^{-1}		Concentration of Si mg g^{-1}		Total content of Si mg $plant^{-1}$	
		Shoots	Roots	Shoots	Roots
$P_0 \times Si_0$		3.50	4.60	4.41	1.01
$P_{3.5}$	Si_{200}	3.64	6.07	4.59	1.58
	Si_{300}	4.11	6.72	6.08	2.08
	Si_{400}	5.67	7.32	9.47	2.64
$P_{7.0}$	Si_{200}	3.63	6.43	5.26	1.99
	Si_{300}	4.60	6.77	7.13	2.28
	Si_{400}	5.89	7.63	10.7	3.43
$P_{10.0}$	Si_{200}	3.69	6.90	6.01	2.55
	Si_{300}	4.62	7.13	7.08	2.78
	Si_{400}	6.04	7.69	11.9	3.77
$P_{13.0}$	Si_{200}	6.02	6.98	11.3	2.72
	Si_{300}	6.07	7.31	11.8	3.00
	Si_{400}	6.33	8.64	12.9	5.44
$LSD_{0.05}$		1.23	0.73	1.93	0.52

Table 7. Concentration and total content of P in shoots and roots of wheat plants at booting growth stage as affected by Si and P interactions in the studied soil

Treatment mg kg^{-1}		Concentration of P mg g^{-1}		Total content of P mg $plant^{-1}$	
		Shoots	Roots	Shoots	Roots
$P_0 \times Si_0$		4.05	3.90	5.10	0.86
$P_{3.5}$	Si_{200}	4.15	4.33	5.23	1.13
	Si_{300}	5.37	4.51	7.95	1.41
	Si_{400}	5.88	4.54	9.82	1.62
$P_{7.0}$	Si_{200}	5.10	4.76	7.60	1.48
	Si_{300}	5.53	5.22	8.57	1.87
	Si_{400}	6.12	5.49	11.1	2.35
$P_{10.0}$	Si_{200}	5.65	4.80	9.45	1.78
	Si_{300}	5.78	5.03	10.2	2.14
	Si_{400}	6.14	5.07	11.8	2.80
$P_{13.0}$	Si_{200}	5.82	5.18	10.9	2.02
	Si_{300}	6.05	5.47	11.7	2.18
	Si_{400}	6.41	5.72	13.1	3.20
$LSD_{0.05}$		0.62	0.94	1.29	0.40

Table 8. Relationship between Si and P concentrations in shoots and roots of wheat plant, and their available concentrations in the studied soil

Treatment	R^2 (Si)		R^2 (P)	
	Shoots	Roots	Shoots	Roots
Si + $P_{3.5}$	0.97	0.80	0.97	0.80
Si + $P_{7.0}$	0.97	0.99	0.97	0.50
Si + $P_{10.0}$	0.99	0.98	0.80	0.93
Si + $P_{13.0}$	0.98	0.96	0.99	0.93
P + Si_{200}	0.50	0.90	0.80	0.63
P + Si_{300}	0.20	0.97	0.96	0.20
P + Si_{400}	0.90	0.62	0.50	0.30

4. CONCLUSION

It could be concluded that application of Si to the clay soil can release P into the soil solution and make it readily available to the plant absorption. So, it could be recommended that selecting good P fertilization design, including time and rate of addition, goes along with values of available Si in the studied soil. In addition, Si fertilization with suitable rate is very important to encourage wheat plant growth and productivity. The treatment of 400 mg Si kg^{-1} in combination with 13 mg P kg^{-1} soil gave the highest growth parameters and total content of both Si and P in the different wheat plants organs.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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