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PEANUT PLANTS RESPONSE TO INCREASE PHOSPHORUS AND CALCIUM UTILIZATION AND MITIGATING HEAT STRESS BY SILICON

Abd El-All, A. E.A.; Abd EL-Rahman, Zeinab M. and Akl, A.A.

Soils, Water and Environment Research Institute, Agricultural Research Center

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ABSTRACT: Silicon (Si) is considered a beneficial element for plant growth and is classified as a bio-stimulant or fertilizer to enhance adaptation to abiotic and biotic stress. Silicon has many noticeable advantages in stressed plants compared to unstressed plants. Silicon can alleviate calcium (Ca) and phosphorus (P) deficiencies. When used effectively, silicon can enhance nutrient uptake, mitigate the effects of P and Ca deficiencies, and improve the productivity of peanut crops under newly reclaimed soil conditions. Two field experiments were conducted in the El-Bostan area, Southern El-Tahrir, El-Behira Governorate (latitude 30.570 N and longitude 30.710 E), Egypt, during the summer seasons of 2020 and 2021 growing seasons to investigate the response of peanut plants to foliar silicon application (potassium silicate (KSi)) at different rates (Si_0, Si_{250} ppm, Si_{500} ppm) and soil application of phosphorus (as mono-ammonium phosphate (MAP), phosphoric acid (PA), or single superphosphate (SSP)) and calcium (calcium nitrate (CaN) or calcium sulfate (CaS)) for the utilization of P and Ca and mitigating heat stress in sandy soil. The experimental results showed that P fertilization significantly increased soil available P (37.6 %) and Ca (39.2%). Also, there is a significant increase in peanut seed yield (12.5%) with MAP application followed by SSP (4.4%) treatments. At the same time, CaS application led to a significant increase in seed N%to7.05 % and Ca content to 7.14%. Elevating the application rate of KSi from 0 to 500 ppm resulted in a significant rise in N, P, Si, and oil content in peanut seeds, along with enhanced oil yield. However, silicon did not affect Ca content in either seeds or straw. The results indicated that the application of MAP and foliar spraying of potassium silicate (KSi) at a rate of 500 ppm (Si_{500}) increased seed yield (19.9%) and straw yields (ton/fed) by 21.7%. Applied MAP with CaN resulted in the highest 100-seed weight (10.2%) under the experimental sandy soil conditions. Overall, the study provides valuable insights into the role of silicon, phosphorus, and calcium fertilization management in optimizing the yield and nutrient content of peanut crops offering implications for agricultural practices and crop management under heat stress conditions due to climate change.

Keywords: Potassium silicate, phosphorus fertilizers, calcium sources, P and Ca utilization, peanut, heat stress

INTRODUCTION

Silicon is the second most abundant element present in the earth's crust varying from 0.1% to 10% in plants. Silicon has not yet been proven to be an essential element for plants; however, it is broadly acknowledged as a beneficial factor for plant growth and development. Silicon can mitigate abiotic stresses, including drought, extreme temperatures (both heat and cold), lodging, salinity, ultraviolet radiation, metal toxicity, and nutritional deficiencies. Additionally, it can alleviate biotic stress, such as plant diseases and insect infestations. Silicon enhances a plant's resilience to both abiotic and biotic stresses through various physiological and biochemical metabolic pathways (Hu *et al.*, 2021). Heat stress (HS) is one of the main abiotic factors that limit agricultural productivity worldwide. An increase in average global temperature will have a significant impact on agricultural output and productivity (Han *et al.*

*Corresponding author:agriahmed@yahoo.com

2009). Due to global warming, the world air temperature by 2100 is expected to be 1.8–4.0 °C higher than current levels (IPCC 2007). Egypt's maximum air temperatures are expected to increase by 2.1°C to 5.7°C and minimum temperatures increasing by 1.5°C to 4.6°C by the 2080s. Extreme heat events will also increase significantly in their severity, frequency and duration, with heatwave events expected to last an additional 9 days to as much as 77 days, with the highest increases occurring in the summer months of July to September (USAID,2018).The rise in the global mean temperature would result in extreme heatwaves events (Perkins-Kirkpatrick and Lewis 2020) which cause severe losses in yield (Telfer *et al.* 2013) due to the reduced resource use efficiency caused by compromised physiological, biochemical, and molecular processes (Wang *et al.* 2018) which will affect all plant growth stages including germination, growth, maturity, fertilization, and productivity (Hasanuzzaman *et al.,* 2013; Firmansyah and Argosubekti, 2019). As a result, the rise in HS will be a serious problem adversely affecting the world's food security. Dreyer *et al*. (2019) highlighted the significance of both air and soil temperatures in influencing peanut yield. The optimal soil temperature for pod formation and development is identified to be between 31 and 33°C, with temperatures exceeding 33°C leading to a notable decrease in the number of mature pods and seed yields. Singh *et al*. (2016) noted that day temperatures surpassing 35°C during the reproductive phase can diminish seed-set, resulting in a reduction of pod numbers and ultimately a decrease in seed yield by 55%. Silicon has many noticeable advantages in stressed plants than in unstressed plants whereas Si nutrition can significantly increase the activities of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and glutathione peroxidase (GPX), in stressed conditions (Etesami and Jeong 2018, Manivannan *et al.* 2016; Soundararajan *et al.*, 2017b).

Silicon enhances stem lignin levels, improving mechanical strength to withstand harsh weather conditions (Hussain *et al*., 2021). Applying silicon can help reduce heat stress damage (Etesami and Jeong, 2018). Adequate silicon in leaves enhances plant heat stress tolerance by regulating nutrient uptake, transpiration, and cell homeostasis, thereby reducing stress and promoting plant growth (Shalaby *et al*., 2021; Liu *et al*., 2019). In water-stressed conditions, Si application improves peanut yield (pod yield per plant, seed yield per plant, and shelling percentage) and increases production (Abdelraouf and Mourad, 2023). In addition to Si application, which promotes nutrient uptake at different growth stages, favors the partitioning of dry mass to pods, and allocates tissue N, P, K, Ca, and Mg to shoots and pods while reducing toxic element uptake and accumulation, potassium, for instance, is beneficial to plant growth, osmotic adjustment, and drought tolerance (Dong *et al*., 2018).Foliar application of silicon, specifically in the form of potassium silicate, significantly increased the phosphorus and calcium content, indicating that silicon can enhance the absorption and concentration of phosphorus and calcium (Abo Basha, Doaa *et al*., 2024, Artyszak *et al*.,2021 and Gad, Doaa *et al*., 2023)

One of the first effects of Si ever studied was its role in nutrient uptake, especially P uptake by plants. Si fertilization increased the yields of barley crops mainly when phosphorus fertilization was limited (Brenchley and Maskell, 1927; Fisher, 1929).

Phosphorus (P) is an important element that significantly affects plants' growth and productivity. The availability of P is very low in soil due to its fixation into organic forms and binding or adsorption by calcium minerals or iron (Fe) oxides, depending on the pH of the soil (Kochian *et al*., 2004). To improve crop performance in low available-P soils, it is essential to focus on two critical strategies: enhancing soil P availability to improve P acquisition efficiency and enhancing P utilization efficiency within the plant's internal organs. Additionally, excessive P stress can occur in greenhouse soils that have been heavily fertilized with P or in hydroponic cultures where a high concentration of P is supplied (Ma, 2004).

The bioavailability of phosphorus (P) in soil is often limited due to its poor solubility, strong sorption, and slow diffusion in most soils. Silicon (Si) is a beneficial element that can alleviate various biotic and abiotic stresses. A comprehensive review of studies on the effects of Si on P nutrition in plants has not been published. The review covers Si uptake, transport, accumulation, roles of phosphate transporters in P acquisition, mobilization, re-utilization, homeostasis, Si's beneficial role in improving P nutrition under P deficiency, and Si's regulatory function in decreasing P uptake under excess P. The results suggest Si mediates P imbalance in plants and present a schematic model to explain its beneficial impact on plant adaptation to P-imbalance stress. Future research should focus on understanding Si's role in regulating P imbalance in plants (Hu *et al*., 2021). The impact of silicon on phosphorus nutrition has been extensively researched. Evidence suggests that silicon plays a significant role in phosphorus nutrition, although the exact nature of this role is still not fully understood. Two main mechanisms of silicon-mediated alleviation of phosphorus deficiency have been proposed: increased root uptake and enhanced utilization of phosphorus within plant tissues. Numerous studies have reported that soil silicon fertilization increased phosphorus uptake (Pavlovic *et al*., 2021). Foliar application of silicon, specifically in the form of potassium silicate, significantly increased the phosphorus and calcium content (Abo Basha, Doaa *et al*., 2024).

Calcium plays a crucial role in peanut seed development, aiding in cell wall formation, cell function, tissue development, and germination processes. Additionally, Ca is necessary for groundnut plants from the time when pegs start to show up, during fruit formation, until the pods are mature. A deficiency of Ca results in high percentages of aborted seeds (empty pods), improperly filled pods, and causes of aborted or shrank fruit (e.g., dark-plumule, production of pods with no seed). The positive impact of gypsum application on peanut vegetative growth may be attributed to its ability to lower soil pH. This pH reduction enhances the availability of essential nutrients such as phosphorus, iron, manganese, copper, magnesium, sulfate, and zinc to the peanut plant roots, each playing a distinct role in promoting plant growth. On some soils with low Ca content, gypsum may also increase seed oil content (Ntare *et al*., 2008). Additionally, applying gypsum in its elemental form improves the movement of phosphorus from the bulk soil to the rhizosphere, enhancing its uptake by the plant (Abd Alla *et al.*, 2009). Conversely, there are indications that high soil Ca levels are associated with lower pod and root rot rates.

A legume such as peanut (*Arachis hypogaea* L.) is a nitrogen fixer that requires more phosphorus than non-leguminous crops. The availability of P improves physiological activity and plays a critical role in enhancing peanut yield (Chirwa *et al*., 2016). The availability of P in legume crops influences, not only, nodule development but also nitrogen acquisition and metabolism (Bogino *et al*. 2006).The application of P fertilizer is considered essential for the growth and development of legume crops as it stimulates root growth, increases nutrient-water use efficiency, and enhances yield.

In Egypt, low peanut yields on newly reclaimed soils are attributed to diminishing soil fertility and alterations in climatic conditions, particularly heatwave occurrences. Therefore, this work aimed to investigate the response of peanut plants to foliar application of silicon as a function for mitigating deficiency and utilization of phosphorus and calcium and adapting plants to heat stress in newly reclaimed sandy soil.

MATERIALS AND METHODS

1. Experimental treatments and design

Two field experiments were carried out in sandy soil in the Southern El-Tahrir region at El Bostan (latitude 30.570 N and longitude 30.710 E), El-Behira Governorate, Egypt, during the two successive growing summer seasons of 2020 and 2021 to investigate the response of peanut to foliar application of silicon at different rates on the utilization of phosphorus and calcium from different sources and mitigate heat stress in newly reclaimed sandy soil. Whereas, the air temperature exceeded 35°C from May to September in 2020 and from June to September in 2021 (https://power.larc.nasa.gov/data-access-viewer/). The main soil chemical and physical properties are presented in Table (1).

Table 1: Soil physical and chemical characteristics of the experimental soil as mean values for 2020/2021 growing seasons.

2020/2021 growing season										
Soil depth (cm)	**Particle size distribution (%)**			**Texture class**	**Available nutrients (mg/kg soil)**			**FC %**	**WP %**	**AW %**
	Sand	**Silt**	**Clay**		**N**	**P**	**K**			
0-15	91.4	3.1	5.5	Sandy	12.0	7.14	85.4	12.2	5.4	6.8
15-30	91.0	4.7	4.3	Sandy	11.10	8.10	61.27	12.0	5.0	7.0
30-45	90.8	5.2	4.0	Sandy	5.95	4.85	40.70	11.3	4.5	6.8

Soil depth (cm)	**Db (g/cm^3)**	**EC (ds/cm)**	**pH**	**Soluble cations and anions (meq/l)**						
				Ca^{+2}	**Mg^{+2}**	**Na^{+}**	**K^{+}**	**HCO_3^{-}**	**SO_4^{-2}**	**Cl^{-}**
0-15	1.44	0.35	8.1	1.00	0.62	1.4	0.48	1.20	0.55	1.75
15-30	1.57	0.41	8.3	1.29	0.65	1.9	0.26	1.24	0.53	2.33
30-45	1.67	0.45	8.5	1.46	0.63	1.9	0.51	1.28	0.67	2.55

A split-split plot statistical design with three replicates was applied, where soil applications of different sources of phosphorus fertilization were laid in the main plots, whereas calcium fertilization sources were allocated in the sub-main plots, and foliar applications of silicon were distributed in the sub-sub plots randomly. The different studied treatments were as follows:

A. Soil application of different phosphorus sources (in Main plots)

1- Mono-ammonium phosphate (MAP) (12-61-0)
2- Phosphoric acid (H_3PO_4) (PA) (61% P_2O_5 and 85% PA)
3- Single Calcium Superphosphate 15.5% P_2O_5 (SSP)

B. Soil application of calcium sources (in Sub-main plots)

1- Calcium nitrate (CaN) (15.5-0-0-26)
2-Calcium sulfate (CaS) gypsum

C. Foliar silicon application as potassium silicates (KSi) (12%K_2O, 30%Si) (in Sub-sub plots)

1- Control (Si_0)
2- 250 ppm Si (Si_{250})
3- 500 ppm Si (Si_{500})

The recommended doses of 45 kg P_2O_5 and 84 kg CaO were applied as superphosphate (15.5% P_2O_5, 25.2% CaO) and calcium sulfate (P2O5 0.5%, CaO 8.4%) for soil application during land preparation, whereas mono-ammonium phosphate (MAP), phosphoric acid (PA), and calcium nitrate (CaN) were injected through irrigation water (fertigation) at the same recommended rates. The foliar application of potassium silicate (KSi) was used as the source of Si. The sub-plot area was 4.2 m^2, including 3 ridges of 80 cm in width and 1.75 m in length with 30 cm between hills. A drip irrigation system was used in this study. The measured discharge rate of the emitter was 3.6 liters/h. Peanut variety Giza 5 was planted in the first week of May. The recommended mineral fertilization of N, P, K, and Ca was applied through irrigation water (fertigation) at equal 5 doses weekly, with the first one applied 15 days after planting. Foliar application of potassium silicate (KSi) occurred twice: first at the vegetative growth (30 days after planting) and second at the pod formation (70 days after planting). Other field practices were performed as recommended by the Field Crop Research Institute and the Agriculture Research Center. The harvest occurred in the second week of August, 120 days post-planting.

2. Sampling and analysis

At the harvesting stage, disturbed surface soil samples were collected from each plot (0-30cm depth) for chemical and physical analyses (Page *et al*., 1982). A 0.5M sodium bicarbonate ($NaHCO_3$) solution with a pH of 8.5 was used to extract the soil's available phosphorus, and a Spectrophotometer was utilized to colorimetrically measure the P concentration using the ascorbic acid method (Page *et al.* 1982). The amount of available Ca in the soil was extracted by ammonium acetate (pH=7) and the concentration of Ca was determined by the Versenate method (Page *et al*., 1982). Peanut seed yield, straw yield (ton/fed), and 100 seed weight were measured at harvesting time. For plant chemical analyses, halfa gram of the oven-dried plant material was subjected to wet digestion with a mixture of sulfuric acid (H_2SO_4) and perchloric acid ($HClO_4$) in a 3:1 ratio, following the method described by Chapman and Pratt (1961). The nitrogen concentration was measured using the macro-Kjeldahl method, while the phosphorus concentration was determined colorimetrically by a Spectrophotometer (Jackson, 1973). The concentrations of calcium and silicon were determined using atomic spectroscopy methods (Page *et al*., 1982).

3. Statistical Analysis

The data obtained were statistically analyzed using the COSTAT Software (CoHort, 1986) statistical package. The mean values for the three replicates of each treatment were interpreted using the analysis of variance (ANOVA). Duncan’s Multiple Range Test was used for comparisons between different sources of variance according to Steel and Torrie (1984).

RESULTS AND DISCUSSION

High-pH (7.9-8.5) soils (calcareous soils) require a more readily available phosphorus source to meet the daily phosphorus uptake by plants; in high-pH soils, phosphorus is fixed and becomes less available to plants. Table (2) indicates that the amount of available phosphorus as a mean value over the two growing seasons was significantly higher with MAP application (7.61 mg kg^{-1}), followed by PA, with no significant differences compared to SSP. This increment may be attributed to the MAP and PA fertilizers having an acidic effect on the soil during multiple applications through irrigation water. This acidification can improve the bioavailability of phosphorus to crops, especially in soils with alkaline pH levels, (Deraoui *et al.*, 2015). However, the mean value of available phosphorus in the two growing seasons was not significantly affected by the application of different calcium sources or silicon rates. The same trend was found for the interaction effects, with no significant interaction effects between the studied variables.

Table 2: Effect of soil application of different P and Ca sources and foliar spray of silicon on soil available P and Ca ($mgkg^{-1}$) content as mean values of the two growing seasons.

Treatments		Available P ($mgkg^{-1}$)				Available Ca ($mgkg^{-1}$)			
Phosphorus sources	**Calcium sources**	**Silicon rate, ppm**							
		Si_0	**Si_{250}**	**Si_{500}**	**Mean**	**Si_0**	**Si_{250}**	**Si_{500}**	**Mean**
MAP	CaN	7.43	9.17	7.67	8.09	19.68	18.97	19.17	19.27
	CaS	7.23	6.97	7.17	7.12	20.03	19.67	19.50	19.73
Mean		**7.33**	**8.07**	**7.42**	**7.61**	**19.86**	**19.32**	**19.33**	**19.50**
PA	CaN	6.03	6.00	5.77	5.93	20.67	20.37	20.53	20.52
	CaS	6.17	6.03	5.87	6.02	20.47	20.13	20.07	20.22
Mean		**6.10**	**6.02**	**5.82**	**5.98**	**20.57**	**20.25**	**20.30**	**20.37**
SP	CaN	5.57	5.87	5.53	5.66	26.23	25.60	25.50	25.78
	CaS	5.50	5.50	5.20	5.40	28.83	28.27	28.43	28.51
Mean		**5.53**	**5.68**	**5.37**	**5.53**	**27.53**	**26.93**	**26.97**	**27.14**
Silicon ×	CaN	6.34	7.01	6.32	6.56	22.19	21.64	21.73	21.86
Silicon ×	CaS	6.30	6.17	6.08	6.18	23.11	22.69	22.67	22.82
Mean		**6.32**	**6.59**	**6.20**	**6.37**	**22.65**	**22.17**	**22.20**	**22.34**
LSD at 0.05 level (as mean values of the two-growing season) for:									
Phosphorus sources(A)		0.54		**A × C**	N.S	**A**	0.83	**A × C**	N.S
Calcium sources (B)		N.S		**B × C**	N.S	**B**	N.S	**B × C**	N.S
Silicon rates (C)		N.S		**A×B×C**	N.S	**C**	N.S	**A×B×C**	N.S
A × B		N.S				A ×B	N.S		

Applications of different sources of calcium significantly increased the amount of available calcium in soils, where soils treated with single calcium superphosphate (SSP) were significantly higher (27.14 $mgkg^{-1}$ Ca) than soils treated with MAP or PA. This may be because SSP contains about 20% calcium compared with MAP and PA. There was no significant effect between different calcium sources on the calcium content in the soil treated with CaS or CaN. Additionally, there were no significant interaction effects between phosphorus and calcium sources and silicon rates on soil available P and Ca, as indicated in Table (2).

Table (3) shows a significant increase in nitrogen content in peanut seeds and straw received with SSP compared to MAP and PA treatments. The nitrogen content increased from 2.23% and 1.53% to 3.08% and 2.06% for MAP and SSP treatments, respectively. Regarding calcium sources, the soil application of CaS resulted in a slight not significant increase in N seed content (2.66%) compared to CaN treatment (2.56%). However, different calcium showed no significant effect on the nitrogen content of peanut straw. Silicon foliar application also causeda significant increase in nitrogen content in peanut seeds and straw from 2.40% and 1.70% to 2.60% and 1.83% for Si_0 and Si_{500}, respectively. These results are consistent with those obtained by El-Shafei *et al.* (2023) who reported a significant increase in nitrogen content in the shoots of wheat plants following foliar application of K_2SiO_3. The study showed an increase of approximately 112% in nitrogen content with K_2SiO_3 compared to the control treatment without $K_2 SiO_3$. This suggests that silicon foliar applications positively impact nitrogen content in plants under drought stress by enhancing the root system and improving water balance in wheat plants. There were no significant interaction effects between different sources of phosphorus and calcium and foliar Si application. However, the interaction effect between phosphorus and silicon treatment. This interaction led to an increase in the nitrogen content of straw from 1.50% at $MAPSi_0$ to 2.22% at $SSPSi_{500}$, representing a relative increase of 48%. This may be due to the role of SSP in lowering soil pH which enhances the availability of nutrients to peanut plants resulting in increasing nutrients by plants (Abd Alla *et al.*, 2009).

Table 3: Effect of soil application of different P and Ca sources and foliar spray of silicon on peanut seeds and straw nitrogen content (%) as a mean values of the two growing seasons.

Treatments		Seed nitrogen, %				Straw nitrogen, %			
Phosphorus sources	Calcium sources	Silicon rate, ppm							
		Si_0	Si_{250}	Si_{500}	Mean	Si_0	Si_{250}	Si_{500}	Mean
MAP	CaN	2.08	2.16	2.25	2.16	1.49	1.51	1.58	1.53
	CaS	2.10	2.15	2.21	2.15	1.50	1.51	1.55	1.52
Mean		**2.09**	**2.16**	**2.23**	**2.16**	**1.50**	**1.51**	**1.57**	**1.53**
PA	CaN	2.29	2.33	2.42	2.34	1.61	1.64	1.69	1.64
	CaS	2.38	2.45	2.64	2.49	1.67	1.72	1.85	1.75
Mean		**2.34**	**2.39**	**2.53**	**2.42**	**1.64**	**1.68**	**1.77**	**1.70**
SP	CaN	2.51	2.68	3.01	2.73	1.78	1.88	2.11	1.92
	CaS	3.05	3.08	3.15	3.09	2.14	2.20	2.22	2.19
Mean		**2.78**	**2.88**	**3.08**	**2.91**	**1.96**	**2.04**	**2.17**	**2.06**
Silicon ×	CaN	2.29	2.39	2.56	2.41	1.63	1.68	1.79	1.70
Silicon ×	CaS	2.51	2.56	2.66	2.58	1.77	1.81	1.87	1.82
Mean		**2.40**	**2.48**	**2.61**	**2.50**	**1.70**	**1.75**	**1.83**	**1.76**
LSD at 0.05 level (as mean values of the two-growing seasons) for:									
Phosphorus sources (A)		0.03		A × C	N.S	A	0.03	A ×C	N.S
Calcium sources (B)		0.03		B × C	N.S	B	N.S	B × C	N.S
Silicon rates (C)		0.16		A×B×C	N.S	C	0.02	A×B×C	N.S
A × B		N.S				A × B	0.19		

The results in Table (4) indicate that phosphorus sources had a significant impact on the phosphorus content in seeds and straw. The phosphorus sources can be ranked in the following descending order: MAP > PA > SSP. Applying MAP as a soil application (through fertigation) significantly augmented the phosphorus content in both peanut seeds and straw. The same trend was found for the effect of foliar KSi application, where the phosphorus content in peanut seed and straw significantly increased with increasing silicon application rates. The Si application promotes nutrient uptake at different growth stages, favors the partitioning of dry mass to pods, and allocates tissue N, P, K, Ca, and Mg to shoots and pods, all of which benefit plant growth (Dong *et al*., 2018). On the other hand, various calcium sources appeared no significant effect on the phosphorus content in peanut seeds and straw. No significant interaction effects were observed, except for the interaction between phosphorus soil application and foliar spray of silicon on the phosphorus content in seeds.

Table 4: Effect of soil application of different P and Ca sources and foliar spray of silicon on peanut seeds and straw P content (%) as mean values of the two growing seasons.

Treatments		Seed P, %				Straw P, %			
Phosphorus sources	Calcium sources	Silicon rate, ppm							
		Si_0	Si_{250}	Si_{500}	Mean	Si_0	Si_{250}	Si_{500}	Mean
MAP	CaN	0.37	0.48	0.61	0.49	0.36	0.36	0.38	0.39
	CaS	0.33	0.37	0.67	0.46	0.36	0.36	0.37	0.38
Mean		0.35	0.43	0.64	0.48	0.36	0.36	0.38	0.39
PA	CaN	0.41	0.56	0.64	0.54	0.35	0.35	0.35	0.39
	CaS	0.36	0.36	0.61	0.44	0.35	0.35	0.36	0.39
Mean		0.39	0.46	0.63	0.49	0.35	0.35	0.36	0.39
SP	CaN	0.37	0.37	0.50	0.41	0.34	0.36	0.38	0.39
	CaS	0.41	0.52	0.56	0.50	0.32	0.36	0.37	0.38
Mean		0.39	0.45	0.53	0.46	0.33	0.36	0.38	0.39
Silicon×	CaN	0.38	0.47	0.58	0.48	0.35	0.35	0.37	0.36
Silicon ×	CaS	0.37	0.42	0.61	0.47	0.34	0.35	0.37	0.35
Mean		0.38	0.45	0.60	0.48	0.35	0.35	0.37	0.36
LSD at 0.05 level (as mean values of the two growing seasons) for:									
Phosphorus sources (A)		0.02		A ×C	N.S	A	0.01	A ×C	N.S
Calcium sources (B)		N.S		B × C	N.S	B	N.S	B × C	N.S
Silicon rates (C)		0.09		A×B×C	N.S	C	0.01	A×B×C	N.S
A × B		0.65				A ×B	N.S		

Table (5) displays the impact of phosphorus sources on calcium content in peanut seeds and straw. The results indicate a significant increase in calcium content in both peanut seeds and the straw is affected by the SSP source. The application of P on peanut seeds showed a similar trend in calcium content when receiving calcium sources. Concerning the effect of silicon rates on the Ca content of peanut seed and straw. The data obtained in Table (5) showed that the maximum calcium content (0.60% and 0.37%) in peanut seeds and straw, respectively, was achieved by applying Si at a rate of 500 ppm. Abo Basha, Doaa, *et al.* (2024), Artyszak *et al.* (2021), and Gad, Doaa, *et al.* (2023) reported that foliar application of silicon significantly increased calcium content by enhancing the absorption and translocation. However, no significant interaction effects were observed among the studied variables.

Table 5: Effect of soil application of different P and Ca sources and foliar spray of silicon on straw and seed Ca content (%) as mean values of the two growing seasons.

Treatments		Seed Ca, %				Straw Ca, %			
Phosphorus sources	Calcium sources	Silicon rate, ppm							
		Si_0	Si_{250}	Si_{500}	Mean	Si_0	Si_{250}	Si_{500}	Mean
MAP	CaN	0.12	0.12	0.13	0.12	1.30	1.37	1.40	1.36
	CaS	0.12	0.12	0.13	0.12	1.28	1.38	1.43	1.36
Mean		0.12	0.12	0.13	0.12	1.29	1.38	1.42	1.36
PA	CaN	0.12	0.13	0.13	0.13	1.32	1.44	1.47	1.41
	CaS	0.12	0.13	0.14	0.13	1.30	1.39	1.47	1.39
Mean		0.12	0.13	0.14	0.13	1.31	1.42	1.47	1.40
SP	CaN	0.15	0.16	0.17	0.16	1.66	1.75	1.87	1.76
	CaS	0.17	0.18	0.19	0.18	1.82	1.93	2.02	1.92
Mean		0.16	0.17	0.18	0.17	1.74	1.84	1.95	1.84
Silicon x	CaN	0.13	0.14	0.14	0.14	1.43	1.52	1.58	1.51
Silicon	CaS	0.14	0.14	0.15	0.14	1.47	1.57	1.64	1.56
Mean		0.14	0.14	0.15	0.14	1.45	1.55	1.61	1.54
LSD at 0.05 level (as mean values of the two growing seasons) for:									
Phosphorus sources (A)		0.7		**A x C**	N.S	**A**	0.05	**A x C**	0.14
Calcium sources (B)		0.06		**B x C**	N.S	**B**	N.S	**B x C**	N.S
Silicon rates (C)		N.S		**AxBxC**	N.S	**C**	N.S	**AxBxC**	N.S
A x B		N.S				**A x B**	N.S		

The data in Table (6) indicated significant increase in the silicon content of seeds due to the treatments of P and Ca sources, and silicon rates. Phosphorus fertilizers notably increased the silicon content in peanut seeds. SSP addition resulted in the highest silicon content compared to that of MAP. Among calcium sources, CaS led to the highest silicon content, while CaN resulted in the lowest one on average over two growing seasons. A higher application of KSi also increased the silicon content in peanut seeds. Specifically, the application of KSi at 500 ppm (Si_{500}) achieved the highest mean values, while the Si_0 treatment had the lowest one. These results are agreed with Dong *et al*. (2018) who reported that Si application promotes nutrient uptake at different growth stages.

Regarding to the interaction effect between phosphorus and calcium fertilization, data recorded in Table (6) cleared that SSP treatment combined with CaS gave the highest significant values of seed silicon content. At the same time, the same interactions showed no significant effect on silicon peanut seed content, except for the interaction effect between P and Ca fertilization. The SSP treatment combined with CaS produced the highest significant values for 100-seed weight, as shown in Table (6). The data presented indicated that MAP had the most superior effect on increasing the weight of 100 peanut seeds (78.52 g) compared to other P fertilizer sources. Additionally, there was a significant difference between different Ca sources in terms of the weight of 100 peanut seeds, with CaN recording the highest weight (77.17 g) compared to CaS (75.89 g). Furthermore, foliar silicon spray significantly affected the weight of 100 peanut seeds. These findings are supported by Abdelraouf and Mourad (2023) who found that the heaviest 100-pod and 100-seed weight were recorded in the silicon treatment at a 60% depletion ratio. These results imply that silicon application may help improve the abiotic stress tolerance of peanuts through the enhancement of yield components such as pod yield per plant, seed yield per plant, and shelling percentage, thereby increasing production under water-stress conditions. On the other hand, there was a significant interaction effect between P and Ca sources, where the 100-seed weight increased from 72.83 g with PA+CaN treatments to 80.25 g with MAP+CaN treatments.

Table 6: Effect of soil application of different P and Ca sources and foliar spray of silicon on peanut seeds Si and 100 seed weight as mean values of the two growing seasons.

Treatments		Seed Si (mgkg^{-1})				100 seed weight (g)			
Phosphorus sources	Calcium sources	Silicon rate, ppm							
		Si_0	Si_{250}	Si_{500}	Mean	Si_0	Si_{250}	Si_{500}	Mean
MAP	CaN	15.58	16.83	17.83	16.75	77.18	80.29	83.27	80.25
	CaS	16.08	17.25	18.08	17.14	74.60	76.58	79.20	76.79
Mean		**15.83**	**17.04**	**17.96**	**16.94**	**75.89**	**78.43**	**81.24**	**78.52**
PA	CaN	16.33	18.33	18.67	17.78	70.86	72.90	74.72	72.83
	CaS	16.33	17.67	18.67	17.56	73.21	75.37	77.51	75.36
Mean		**16.33**	**18.00**	**18.67**	**17.67**	**72.03**	**74.13**	**76.12**	**74.09**
SP	CaN	21.00	22.50	23.67	22.39	75.75	78.09	81.46	78.43
	CaS	23.25	25.00	26.00	24.75	72.51	75.59	78.49	75.53
Mean		**22.13**	**23.75**	**24.83**	**23.57**	**74.13**	**76.84**	**79.97**	**76.98**
Silicon ×	CaN	17.64	19.22	20.06	18.97	74.59	77.09	79.82	77.17
Silicon ×	CaS	18.56	19.97	20.92	19.81	73.44	75.84	78.40	75.89
Mean		**18.10**	**19.60**	**20.49**	**19.39**	**74.02**	**76.47**	**79.11**	**76.53**

LSD at 0.05 level (as mean values of the two growing seasons) for:							
Phosphorus sources (A)	0.14	**A x C**	N.S	**A**	0.29	**A x C**	N.S
Calcium sources (B)	0.11	**B x C**	N.S	**B**	0.29	**B x C**	N.S
Silicon rates (C)	0.31	**AxBxC**	N.S	**C**	0.69	**AxBxC**	N.S
A × B	0.65			**A x B**	0.19		

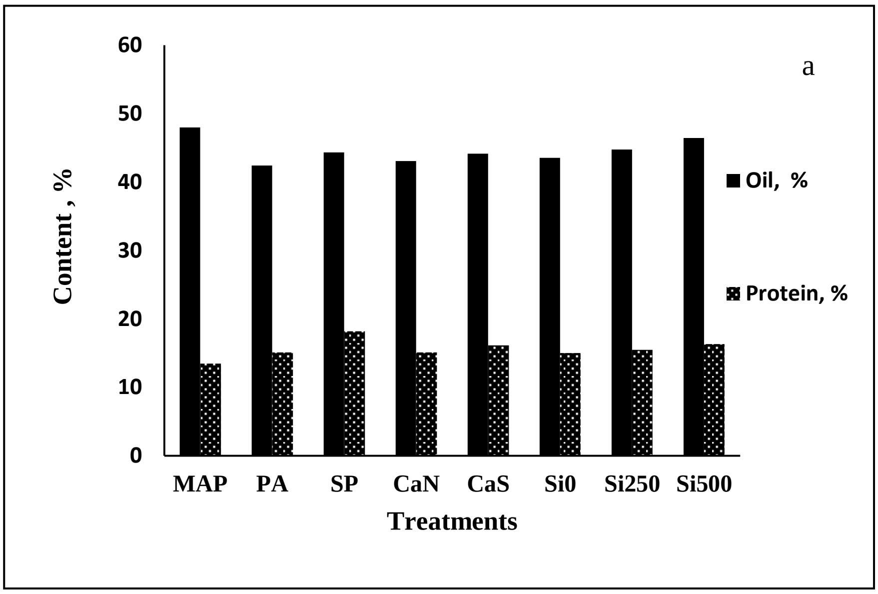
Table (7) shows that the application of different sources of P had a significant impact on peanut seed yield. The yield increased from 1.36 tons per fed with PA treatment to 1.42 and 1.53 tons per fed with that of SSP and MAP, respectively. This indicates that MAP application resulted in a higher seed yield compared to SSP and PA. Additionally, CaN significantly augmented peanut seed yield compared to CaS, with yields increasing from 1.41 to 1.45 tons per fed for CaS and CaN respectively. This may be ascribed to that calcium was more readily available in the form of CaN compared with CaS. In agreement with the obtained findings, Hamza *et al*. (2021) found that peanut plants treated with CaN displayed a 57.32 % increase in seed yield. The application of calcium increased the number of filled pods, leading to higher seed and pod yields, while phosphorus promoted vegetative growth (Kamara *et al.*, 2011). Seed yield showed a significant increase with higher foliar silicon application rates (Table 7). These results are consistent with Stephano *et al.* (2020) who found that maize treated with S-Si1 (Silicon fertilizer + no straw return) had an increase in the straw by 10.6% and a grain yield by 4.8% compared to S-Si0 (no Silicon fertilizer + no straw return). Silicon application also enhanced peanut yield components (shell yield per plant, seed yield per plant, and shell rate) and improved yield under water stress conditions. These findings suggest that applying silicon may enhance drought tolerance in peanuts by improving water absorption capacity (Abdelraouf and Mourad, 2023). The study also revealed significant interaction effects between various sources of phosphorus and/or calcium and foliar silicon application rates. Specifically, the application of MAP+Si_{500} and CaN+Si_{500} resulted in the highest increase in seed yield.

Table 7: Effect of soil application of different P and Ca sources and foliar spray of silicon on seed and straw peanut yields (ton.fed^{-1}), as mean values of the two growing seasons.

Treatments		**Seed yield (ton/fed)**				**Straw yield (ton/fed)**			
Phosphorus sources	**Calcium sources**	**Silicon rate, ppm**							
		Si_{0}	**Si_{250}**	**Si_{500}**	**Mean**	**Si_{0}**	**Si_{250}**	**Si_{500}**	**Mean**
MAP	CaN	1.54	1.58	1.62	1.58	4.44	4.79	4.73	4.65
	CaS	1.43	1.47	1.53	1.47	4.37	4.56	4.93	4.62
Mean		**1.49**	**1.53**	**1.57**	**1.53**	**4.41**	**4.68**	**4.83**	**4.09**
PA	CaN	1.29	1.34	1.41	1.35	3.90	4.03	4.16	4.03
	CaS	1.33	1.37	1.40	1.37	4.03	4.13	4.25	4.14
Mean		**1.31**	**1.36**	**1.40**	**1.36**	**3.97**	**4.08**	**4.20**	**4.64**
SP	CaN	1.39	1.43	1.49	1.44	4.24	4.23	4.46	4.31
	CaS	1.35	1.39	1.44	1.39	4.16	4.26	4.28	4.23
Mean		**1.37**	**1.41**	**1.47**	**1.42**	**4.20**	**4.25**	**4.37**	**4.27**
Silicon ×	CaN	1.41	1.45	1.51	1.45	4.19	4.35	4.45	4.33
Silicon ×	CaS	1.37	1.41	1.45	1.41	4.19	4.32	4.49	4.33
Mean		**1.39**	**1.43**	**1.48**	**1.43**	**4.19**	**4.33**	**4.47**	**4.33**
LSD at 0.05 level (as mean values of the two growing seasons) for:									
Phosphorus sources (A)		0.01		**A × C**	0.18	**A**	0.08	**A × C**	0.66
Calcium sources (B)		0.01		**B × C**	0.13	**B**	N.S	**B × C**	N.S
Silicon rates (C)		0.02		**A×B×C**	N.S	**C**	0.10	**A×B×C**	N.S
A × B		N.S				**A x B**	N.S		

Straw yield varied significantly with different P sources. The highest straw yield (4.64 ton/fed) was observed in soil fertilized with MAP compared to that received PA and SSP treatments (Table 7). These results align with findings reported by Kamara *et al*. (2011) who noted that phosphate fertilizer application increased total dry weight in both seasons. The increase in yield can be attributed to phosphorus's role in promoting the development of an extensive root system, facilitating water and nutrient absorption from deeper soil layers. Consequently, this enhanced nutrient uptake can improve the plant's ability to produce more assimilates, leading to higher biomass. In addition, the foliar application of Si up to 500 ppm (Si_{500}) significantly increased the straw yield of peanuts (Table 7). Our findings align with Gomaa *et al*. (2021), who demonstrated that foliar application of potassium silicate at a concentration of 1500 mg/l resulted in the highest weight of 100 pods, number of pods /plants, pod yield, biological yield, and straw yield (ton/fed). Silicon is crucial for the growth and development of plants, as it enhances root growth and activity, likewise facilitating the absorption of water and nutrients by crops (Artyszak, 2018). However, calcium sources did not have any significant effect on peanut straw yield. There was no significant interaction effect observed among the studied variables, except for the interaction between different phosphorus sources and foliar application of silicon. In this case, straw yield increased from 3.97 ton/fed with the PA Si_0 treatment to 4.83 tons ton/fed with the MAP Si_{500} treatment.

Fig. 1 (a and b) illustrated that protein (%) and protein yield (kgfed^{-1}) differed with different sources of P and Ca with relative increases of 35.08 and 6.9 % for P and Ca sources, respectively. Foliar spray of silicon positively increased protein yield (kgfed^{-1}) for the treated plants compared with the untreated ones, where protein (%) increased from 15.01 % at Si0 to 16.23 % at Si500, the same trend was found for protein yield. Where, the higher oil content (%) and oil yield (kgfed^{-1}) were obtained by applying MAP, CaS, and the higher silicon foliar application rates (Si_{500}). Furthermore, there was a significant positive correlation (R^2= 1) between Si foliar spray rate and seed oil yield and protein yield (kgfed^{-1}) (Fig. 2, a and b).



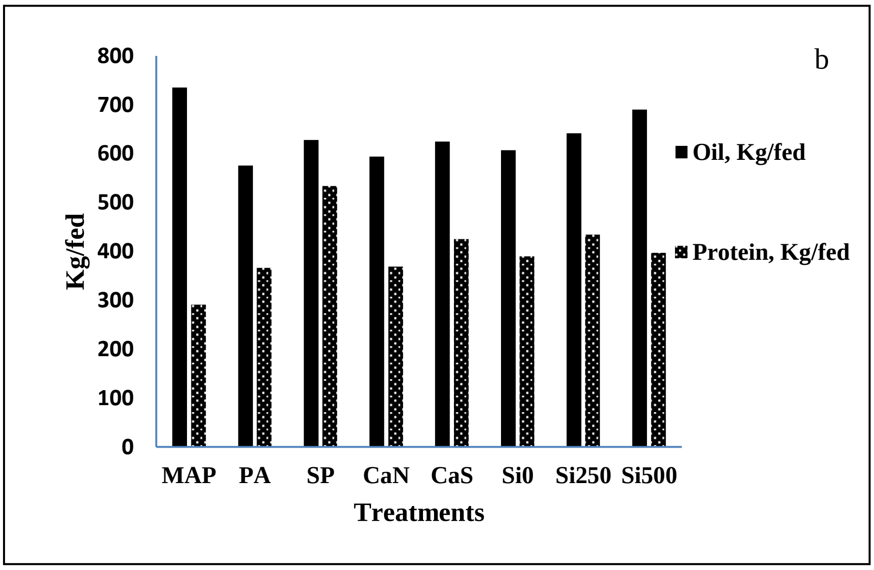


Fig (1): Effect of different phosphorus and calcium fertilizer sources and foliar spray of different silicon rates on peanut seed oil and protein (%), oil, and protein yield (kg/fed).

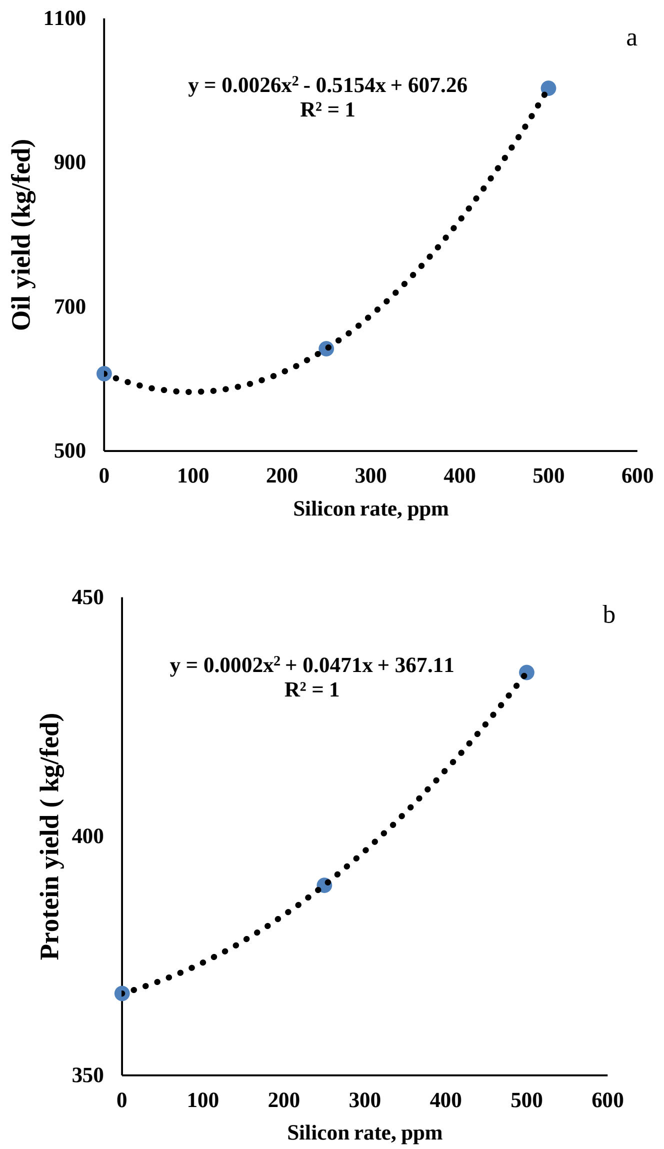


Fig 2 (a and b): Correlation between silicon foliar application rates and peanut seed oil (a) and protein yield (b) (Kg/fed)

CONCLUSION

The study highlighted the significant impact of silicon, phosphorus, and calcium on the growth and yield of peanut crops. The field experiment results indicated a notable rise in available phosphorus (P) and calcium (Ca) from different sources under newly reclaimed sandy soil conditions, as well as an increase in seed yield and 100-seed weight when MAP was applied followed by SSP fertilizers. The application of calcium nitrate CaN resulted in a significant increase in seed nitrogen (N) and calcium content. The study also revealed the impact of silicon rates on phosphorus and calcium utilization by peanuts, which significantly influenced 100-seed weight, seed yield, oil content, and protein content under increased heat stress due to climate change. Peanuts treated with potassium silicate at a rate of 500 ppm led to a significant increase in nitrogen, phosphorus, silicon, and oil content in peanut seeds, along with an increase in oil yield, enhancing peanut growth under abiotic stress. However, silicon did not affect calcium content in either seeds or straw. Furthermore, the findings revealed that applying ($MAP+Si_{500}$) or ($CaN+Si_{500}$) increased seed and straw yield (ton/fed), while the application of MAP with CaN resulted in the highest 100-seedweightunderthe studied sandy soil. Overall, the study provides valuable insights into the role of silicon, phosphorus, and calcium fertilization management in optimizing the yield and nutrient content of peanut crops offering implications for agricultural practices and crop management under heat stress conditions due to climate change.

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إستجابة نباتات الفول السوداني لزيادة الإستفادة من الفوسفوروالكالسيوم وتخفيف الإجهاد الحراري بواسطة السيليكون

أحمد إسماعيل أحمد عبد العال، زينب مصطفى عبد الرحمن، أيمن عطفى عقل

معهد بحوث الأراضى والمياة والبيئة - مركز البحوث الزراعية

الملخص العربى

إجريت تجربتان حقليتان بمنطقة البستان- جنوب التحرير محافظة البحيرة في موسمى صيف 2020 و 2021 لدراسة إستجابة الفول السوداني لزيادة الإستفادة من الفوسفوروالكالسيوم وتخفيف الإجهاد الحراري بواسطة السيليكون. و كان تصميم التجربة قطاعات منشقة مرتين،حيث كانت المعاملات الرئيسية هي مصادر الفسفور(فوسفات أحادي الأمونيوم MAP، حمض الفسفوريك PA، سوبر فوسفات أحادى الكالسيوم SP) أما القطع التحت رئيسية وضع بها مصادر الكالسيوم (نترات الكالسيوم CaN، كبريتات الكالسيوم CaS) بينما القطع تحت تحت الرئيسية وضع بها معدلات الرش بسليكات البوتاسيوم (كنترول (Si_0) و ٢٥٠ جزء في المليون (Si_{250}) و ٥٠٠ جزء في المليون(Si_{500}). أظهرت النتائج زيادة معنوية في كلا من تركيز الفسفورالميسر وكان ترتيب المعاملات MAP> PA>SP أما بالنسبة للكالسيوم الميسر في التربة الرملية فكانت تتبع الترتيب التالى SP>PA>MAP. كانت هناك زيادة معنوية فى محصول الحبوب طن/فدان، وزن ١٠٠ بذرة مع المعاملة MAP يليها SP. أدى استخدام كبريتات الكالسيوم (CaS) إلى زيادة كبيرة في محتوى النيتروجين والكالسيوم في البذور. كما أدت زيادة معدلات الرش بسيليكات البوتاسيوم من ٠ إلى ٥٠٠ جزء في المليون إلى زيادة كبيرة في محتوى النيتروجين والفسفور والسيليكون و محتوى الزيت في بذور الفول السوداني، وكذلك محصول الزيت كجم/فدان ومع ذلك، لم يكن للسيليكون أي تأثير على محتوى الكالسيوم في البذور أو القش. بالإضافة إلى ذلك، أظهرت النتائج أن معاملة MAP Si_{500} أدت إلى زيادة محصول البذور (طن/فدان) وكذلك محصول الزيت والبروتين (كجم/فدان). كما أظهرت معاملة MAP مع CaN أعلى القيم لوزن ١٠٠ بذرة في ظل ظروف التربة الرملية.

الكلمات المفتاحية: سيليكات البوتاسيوم، الأسمدة الفوسفاتية، مصادر الكالسيوم، الإستفادة من البوتاسيوم والكالسيوم، الفول السوداني، الإجهاد الحراري.