International Journal of Plant & Soil Science

Volume 37 Issue 10, Page 1-21, 2025; Article no.IJPSS.144817
ISSN: 2320-7035

The Interaction between Nano Silica and Phosphorus, Applied Using Various Techniques in Calcareous Soil, Affects the Productivity of Wheat and Maize Crops

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Authors' contributions

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i105757

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/144817

Original Research Article

Received: 17/07/2025
Published: 27/09/2025

ABSTRACT

Calcareous soils, abundant in calcium carbonate, are prevalent in most arid and semi-arid environments. When phosphorus fertilizer is applied to calcareous soils, a sequence of fixation processes occurs that progressively diminishes the fertilizer's solubility and, ultimately, its accessibility to plants. This study aims to determine the effects of nano silica (derived from rice husk) and phosphorus at different rates, which are applied by various techniques to wheat and maize crop productivity, as well as the status of silicon and phosphorus in both crops under calcareous soil conditions. Therefore, we performed a field study at the El-Nubaryia Agricultural Research Station, the Agricultural Research Center (ARC), Egypt, on studied crops. The split-split plot design was used; each treatment was replicated three times. The main plots had three nano silica rates: without nano-silica (NSi0), 2 mM SiO_2 (NSi1), and 4 mM SiO_2 (NSi2). The sub-main

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Cite as: *Heba Y. A. Morsy, Wafaa, M.T. El-Etr, and Hanaa A. Zein El-Abdeen. 2025. "The Interaction Between Nano Silica and Phosphorus, Applied Using Various Techniques in Calcareous Soil, Affects the Productivity of Wheat and Maize Crops". International Journal of Plant & Soil Science 37 (10):1–21. https://doi.org/10.9734/ijpss/2025/v37i105757.*

plots had four phosphorus rates for soil application: without P (P0), 8 (P1), 11 (P2), and 13 Kg P fed^{-1} (P3); for foliar application, the rates were 25 (P1), 50 (P2), and 100 mg P L^{-1} (P3). The sub-sub-main plots consisted of two application techniques: soil application (SA) and foliar application (FA) on the plant. The experimental treatments showed that, compared to the control, the yield components of wheat and maize crops (yield, straw or stover, and grain) increased significantly. This tendency was also observed in the overall silicon and phosphorus total content. The most effective treatment, found as NSi2P3 using the FA technique, yielded 3610 and 4449 Kg fed^{-1} for grain wheat and maize, respectively. Additionally, these treatments improved the chemical properties of calcareous soil by reducing the pH to 7.3 and the $CaCO_3$ content to 13.8% after wheat harvest, which enhanced the soil's accessibility to phosphorus (P) and silicon (Si). Finally, we can conclude that the use of nano silica made from agricultural waste may help reduce expenses by decreasing the amount of phosphate fertilizers required in calcareous soil. Therefore, using nano silica with phosphate fertilizers as a foliar application on wheat and maize plants in calcareous soil increased crop productivity and phosphorus efficiency. Additionally, this study helps the environment by managing waste and reducing the use of chemicals in agriculture.

Keywords: Calcareous soil; nano silica; phosphorus; application techniques; nutrients availability; wheat; maize.

1. INTRODUCTION

The primary goal of the methods the Egyptian administrations have implemented is to reduce the food gap brought on by population growth and land degradation. Reclamation soil is essential to reducing the food gap caused by land degradation and population increase, as the agricultural sector is crucial to Egypt's economy and the country's population continues to rise (Abd El-Kawy et al., 2019). Due to minimal leaching, calcareous soils predominated in arid and semi-arid areas. More than 15% additional $CaCO_3$ and at least 5% additional carbonate in the underlying layer, along with a calcic horizon, are characteristics of calcareous soils (FAO, 2022). Such soil presents several challenges for crop cultivation and production, including a high $CaCO_3$ content that lowers soil fertility and nutrient availability, surface crust formation that hinders crop germination and growth, and, lastly, a low amount of available moisture (Abdel-Aal et al., 1990; Pearce et al, 1999). According to Wahba et al. (2019), calcareous soils often have low levels of accessible nitrogen and organic matter. In addition, a high pH level causes phosphate to become unavailable (forming inaccessible calcium phosphates as apatite) and often lowers the availability of micronutrients like iron and zinc. The nutritional disparity between calcium and magnesium and potassium may also lead to issues with their nutrition. Because of how soil pH affects nutrient availability and chemical processes that cause nearly all nutrients to be lost or fixed, nutrient management for calcareous soils is different from that in non-calcareous soils (Akhtar et al., 2016).

Numerous studies make use of nanoparticles; the characteristics of many nanoparticles differ greatly from those of micro- and macro-materials. Particles with at least one dimension between 1 and 100 nm are known as nanoparticles (NPs). (Hashmi et al., 2016).Since their larger surface area improves solubility and surface reactivity, they can have a greater positive impact on physio-chemical characteristics than bulk materials. One of the main anthropogenic factors contributing to global eutrophication issues is the extensive use of mineral nitrogen, phosphorus, and potassium (NPK) fertilizers. In the meanwhile, nanotechnology reduces pollutants and the hazards associated with chemical fertilization while improving fertilizer application efficiency (Naderi et al., 2011). Because of their unique physicochemical properties, nanoparticles may boost plant metabolism (Giraldo et al., 2014). As stated by El-Awady et al. (2022), nano fertilizers are as well less expensive and needed in smaller quantities than chemical fertilizers, but they have the same needs. Grain quality benefits might result from the use of nano fertilizer, which promotes plant growth, development, and antioxidant activity, improves yield, increases nutrient usage efficiency, and lowers soil pollution (Elekhtyar et al., 2022). Conventional production can employ various Si sources as fertilizer. One of these sources, nano-Si, can help boost the amount of Si available in soils that naturally lack bioavailable Si. Because of its large surface area, nano-Si may more easily release Si into the soil solution, allowing wheat to absorb it (Taskin et al., 2023; Akca et al., 2023; Gonc et al., 2024).

After harvests, Si accumulates; this can be especially advantageous for wheat crops (Taskin et al., 2023; Akca et al., 2023). Numerous crops, including maize (Castro & Crusciol, 2013) and wheat (Provance-Bowley et al., 2010), have demonstrated positive benefits of silicate treatment on crop growth and yield. On top of that, maize (Zea mays L.) grows more readily when nano-silicate is added to the soil (Yuvakkumar et al., 2011). Additionally, according to Elekhtyar and AL-Huqail (2023), foliar application of silicon nanoparticles (SiNPs) exhibits favorable impacts on yield and growth, particularly at higher concentrations. In a study by Kim et al. (2002), this treatment thickens the rice leaves' epidermal cell walls. Changes in plant architecture, including increased erectness, improved leaf angle and light interception, avoidance of excessive self-shading, delayed senescence, increased structural rigidity of the tissues, enhanced photosynthesis, and reduced lodging, are associated with the highest growth and grain production in plants supplied with Si (Gong & Chen, 2012; Ma and Yamaji, 2008). Si deposits in the cell walls of different plant organs are responsible for these advantageous effects, along with additional processes (Ma & Yamaji, 2006). Excessive Si deposition in tissues creates a physical barrier that increases the tissues' stiffness and strength. Furthermore, ecological factors, such as the impact of Si on the accumulation of nutrients in plant tissues, are typically absent (Liao et al., 2020).

Moreover, phosphorus (P) is one of the most important nutrients for all plant and animal life, based on Rezakhani et al. (2019). Large amounts of both organic and inorganic P are present in most agricultural soils, but they are mostly stationary and inaccessible to plants. Only an extremely small amount of phosphorus (P) is readily accessible to plants, accounting for 0.1% of the total phosphorus, and many agricultural soils are P-deficient due to the high reactivity of phosphorus with certain metals, such as calcium (Ca), iron (Fe), and aluminum (Al). This reactivity leads to the formation of metal complexes that precipitate or adsorb between 75% and 90% of the phosphorus in the soils (Adesemoye & Kloepper, 2009). Large quantities of chemical P fertilizers must be applied often to agricultural soils to improve the availability of phosphorus for plants (Ohno et al., 2005). However, by reacting with Ca^{2+} ions and creating minerals like calcium phosphate ($CaHPO_4$) in the soil, significant levels of P in fertilizers may be instantly transformed into insoluble phosphate that plants cannot use (Zaidi et al., 2009). Furthermore, excessive or ongoing long-term use of chemical fertilizers, such as chemical-P fertilizers, pollutes the environment and degrades soil quality by negatively affecting the soil's structure, microflora composition, and other characteristics (Gyaneshwar et al., 2002). Wahid et al. (2020) highlight that calcareous soils' low phosphorus availability hinders long-term cereal crop productivity, as P becomes immobilized due to increased calcium levels, affecting P shortage and low efficiency. Also, Korkmaz et al. (2010) found that increasing P rates in calcareous soils significantly increased wheat dry matter production and P content, highlighting the importance of phosphorus in plants for protein production, energy generation, and membrane structure preservation. According to Razaq et al. (2017), P aids in cell division, enzyme activation and inactivation, and the metabolism of carbohydrates. Wahid et al. (2020) noted that plants with more P and K applied foliar had higher levels of dry matter and chlorophyll. Due to the increased inefficiency of phosphorus caused by calcium carbonate ($CaCO_3$), higher rates of fertilizer are necessary for crop productivity.

Enhancing plant health and production in wheat and maize requires optimal P and Si nutrition. Although both are critical for plant development and resistance, their interdependent functions are frequently disregarded. The Si-P interaction is very significant because Si can change P solubility, compete for adsorption sites on soil minerals, and improve root exudation mechanisms that affect P release (Akca et al., 2023). These interdependent relationships emphasize how crucial it is to manage Si and P together, especially in calcareous soils where intricate chemical processes frequently restrict nutrient availability (Gunes et al., 2025). This work evaluates Si and P simultaneously due to their significant interactions in plant absorption and utilization (Taskin et al., 2023). Research indicates that while P treatment increases the plant's need for Si, the application of Si enhances the absorption of both elements (Akca et al., 2023). To optimize the advantages of these interactions, these findings highlight the necessity of coordinated nutrition management. Due to their high intake, Si-accumulating crops like rice and wheat deplete soil Si reserves. This depletion can then impact P dynamics through a variety of processes, such as alterations in soil pH, the breakdown of organic matter, and changes in nutrient availability brought on by roots (Schaller et al., 2019). Furthermore, Schaller et al. (2022) revealed that the amorphous Nano-Si derived from the husk may be classified as biogenic Si. Nano-Si may be a usefuly of silicon for plants' Si requirements and for boosting P utilization efficiency. Similarly, Taskin et al. (2022) claimed that the application of Nano-Si improved phosphorus usage efficiency. Therefore, less P fertilizer may be utilized when Nano-Si is employed. Excess P will have a less negative impact on Si if fewer P fertilizers are used. The relationship between P and Si is one-sided. P fertilization decreases the plant's absorption of Si, whereas Si treatments increase the plant's uptake of P.

On the other hand, wheat (Triticum aestivum L.) is categorized first among cereals owing to its importance as the major staple food crop worldwide (Iqbal et al., 2021). It is acknowledged as one of the most significant grain crops, particularly in arid and semi-arid regions where rain is necessary for cultivation. Abdel-Mageed et al. (2019) found that better planting techniques and varieties increased Egypt's wheat yields by 5.8 times (6.7 billion kg) between 1961 and 2017. Egypt is now one of the world's largest importers of wheat due to population growth and increased demand for the grain. About 12 million tonnes of wheat were imported by the nation in 2016–2017, which is almost 1.3 million tonnes in excess of the average for the past five years (FAOSTAT, 2022). This pattern is probably going to continue, and by 2028, imports may surpass 15 million tonnes. Therefore, to address the production-to-consumption gap, Egypt urgently needs to boost wheat growing. However, wheat cropping methods and soil physicochemical characteristics has changed significantly as a result of the long-term application of NPK fertilizers on calcareous soils (Das et al., 2021).

In addition, maize (Zea mays L.) accounts for one-third of grain output (IGC, 2012). A staple grain that is essential for human and animal nutrition, maize also helps meet the energy demands of the biofuel sector (Misbah et al., 2022). Furthermore, according to Osman et al. (2018), maize is a crucial cereal crop grown in Egypt and has a significant role in the country's economy. In Egypt, there is an estimated 45% discrepancy between maize output and consumption (Ouda et al., 2016). Recent years have seen a drop in agricultural output due to a fall in soil fertility (Sharif et al., 2004). It has been determined that the most important factor restricting maize productivity among the several production parameters is nutrient management.

Previous studies primarily focused on the influence of nano silica on the growth of wheat and maize under various conditions; however, there is limited understanding of the impact of nano silica in conjunction with varying P rates on the plant growth in calcareous soil. Therefore, this study aims to demonstrate how nano silica, derived from rice husks, combined with different phosphorus rates and application techniques in calcareous soil, affects the yield of wheat and maize, the total silicon and phosphorus content in these plants, and the specific chemical properties of the soil.

2. METHODLOGY

2.1 Description of the Research Location

In the two consecutive seasons of 2021–2022, the field experiment was conducted on calcareous soil at El-Nubaryia Agricultural Research Station, the Agricultural Research Centre (ARC), Egypt. The station is located at 30° 54' N, 29° 57' E, and 25m above sea level. Cool winters and hot, dry summers characterize the arid environment of the experimental region. Table 1 shows the results of an examination of the chemical characteristics and nutrient availability of the surface soil sample (0–30 cm), as described by Page et al. (1982).

Table 1. Some physicochemical properties of the experimental soil

Particle size distribution		Soil chemical properties		Available nutrients (mg Kg^{-1})	
Sand	64.6	OM %	0.65	N	172
Silt	11.5	pH*	8.12	P	14.9
Clay	23.9	EC**	2.65	K	211
Texture	Sandy clay loam	$CaCO_3$ %	26.5	Si	91.9
Soluble cations (meq L^{-1})		**Soluble anions (meq L^{-1})**			
Ca^{2+}	8.84	CO_3^{2-}	Nd		
Mg^{2+}	8.32	HCO_3^-	7.34		
Na^+	7.80	Cl^-	8.30		
K^+	1.55	SO_4^{2-}	10.9		

**pH (Soil-water suspension ratio, 1:2.5), **EC dS m^{-1}(soil paste extract)*

2.2 Experiment Design and Treatments

Trials in the field were conducted to evaluate the effects of varying rates of nano silica and phosphorus by two application techniques on the wheat and maize yield, nutrition status in plants, pH, $CaCO_3$ %, and nutrient availability in calcareous soil. An experiment was planned in a split-split plot with three replications, including three different amounts of nano silica: 0, 2, and 4 mM SiO_2 were used in the main plots (NSi0, NSi1, and NSi2). Four phosphorus (P) rates in the form of phosphoric acid were included in the sub-main plots: 0%, 60 % (8 Kg P fed-1), 80% (11 Kg P fed-1), and 100% (13 Kg P fed-1) for soil application (P0, P1, P2, and P3) based on the recommended dose of P fertilizer for both wheat and maize crops. Foliar application on the plants was conducted at rates of 0, 25, 50, and 100 mg P L^{-1}. The sub-sub-main plots included two application techniques: soil application (SA) and foliar application on the plant (FA). In both seasons, these treatments were administered twice, at 30 and 60 days after the date of sowing.

2.3 Agricultural Practices and Fertilizing Systems

The land area was prepared, and the standard of agricultural practices was used based on crop specifications. It was then prepared for the automated planter by being tilled with a rotavator. The testing crops were selected to be wheat (*Triticum sativum var.* Giza 168) in the winter and maize (*Zea mays L. c.v*. hybrid 10) in the summer. Additionally, 100 and 120 kg N fed-1 in the form of ammonium nitrate (33% N) were given to the wheat and maize plants, respectively, in three doses. Furthermore, at sowing and 30 days following planting, 50 kg fed^{-1} of potassium sulphate (48% K_2O) was administered in two equal dosages.

2.4 Assessment of Post-harvest Plant

Each plot was harvested for one square meter of standing wheat and maize crops after the plants were fully grown. Yield components of both tested crops (Biological, straw or stover, and grain yields (kg fed-1)) were calculated. A combination of sulphuric acid and hydrogen peroxide was used to digest samples of plants from each treatment after they had been dried in an oven at 70°C for 48 hours and pulverized in a stainless-steel mill. Finally, as explained by Page et al. (1982), little portions were collected and examined to determine the overall amounts of phosphorus and silicon in straw or stover and grains.

2.5 Assessment of Soil Properties

After harvesting both crops, soil samples were collected from the experimental site at depths of 0 to 30 cm. Following air drying, these samples were passed through 2 mm sieve pores. In accordance with Cottenie et al. (1982), soil samples were analysed as follows: the pH of a soil water suspension at a ratio of 1:2.5, the content of $CaCO_3$ % measured by calcimeter, and the availability of Si and P were also determined.

2.6 Statistical Analysis

Every data set was statistically examined throughout the seasons using the methodology of Snedecor and Cochran (1980). Using the least significant difference (LSD) test with a probability of 0.05, the significance of differences between treatments was evaluated. According to Freed et al.'s research (1989), the "MSTAT-C" computer software was ultimately utilized for all statistical analyses. The program Microsoft Excel was used to perform the correlations.

3. RESULTS AND DISCUSSION

3.1 Response of Wheat and Maize Yields to Different Applied Treatments

The results in Table 2 illustrate the yield components, including biological yield, straw or stover yield, and grain yield for wheat and maize cultivated on calcareous soil under the assessed treatments. Data demonstrate that the mean value of plant growth parameters significantly rose as nano silica rates increased. The high rate of nano silicon (NSi2) was the most effective treatment for increasing biological, straw, and grain yields for wheat; it resulted in increases of 23, 21 and 27%. A similar pattern was observed in maize, showing increases of 13, 14, and 15%, respectively. This increase may be due to silicon's capacity to strengthen and harden plant tissue, which protects plants while simultaneously improving their photosynthesis. Additionally, it facilitates better nutrient uptake and transport by plants. Silicon also contributes to improved growth, evaporation and transpiration efficiency, chlorophyll concentration per leaf area, and product quality

Table 2. Yield components of wheat and maize in calcareous soil as influenced by nano silica and phosphorus treatments at two application techniques

NSi Rates	P Rates	Wheat growth parameters (Kg fed^{-1})						Maize growth parameters (Kg fed^{-1})					
		Biological		**Straw**		**Grain**		**Biological**		**Stover**		**Grain**	
		Application techniques											
		SA	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**
NSi0	**P0**	7140	7108	5134	4989	2006	2118	9333	10710	6359	7425	2497	2774
	P1	8210	7980	5982	5373	2228	2607	10167	11750	6812	8069	3106	3221
	P2	9296	9128	6742	6276	2554	2852	11217	12850	7519	9037	3179	3401
	P3	10085	10206	7123	6961	2962	3245	13750	12444	9276	8532	3518	3527
Mean of NSi0		8644		6073		2572		11528		7879		3153	
NSi1	**P0**	8794	8420	6126	5805	2668	2615	9722	11550	6336	7925	2979	3149
	P1	9761	9548	6860	6395	2901	3153	11333	12067	7905	8111	3141	3389
	P2	10309	10976	7162	7587	3147	3389	12722	13250	9002	9143	3345	3517
	P3	11047	11340	7567	7931	3480	3409	13950	14417	9435	10331	3759	3991
Mean of NSi1		10025		6929		3095		12376		8523		3409	
NSi2	**P0**	8896	9744	6032	6969	2865	2775	10389	11700	6731	8012	3124	3221
	P1	9861	10752	6689	7448	3172	3304	12333	12850	8553	8860	3453	3442
	P2	10462	11032	7067	7550	3394	3482	13290	13333	9160	9339	3589	3728
	P3	11565	12460	8018	8850	3546	3610	14250	15833	9832	11572	3835	4494
Mean of NSi2		10596		7328		3269		12997		9007		3611	
Mean of AT		9619	9891	6709	6845	2910	3047	11871	12730	8077	8863	3294	3488
Mean of P	**P0**	8350		5843		2508		10567		7131		2957	
	P1	9352		6458		2894		11750		8052		3292	
	P2	10200		7064		3136		12777		8866		3460	
	P3	11117		7741		3375		14107		9830		3854	
LSD at 0.05	**NSi**	421		232		182		281		237		50.6	
	P	223		287		156		209		191		67.4	
	AT	161		160		74.7		142		164		67.8	
	NSi*P*AT	558		553		259		491		569		235	

SA (Soil application), FA (foliar on the plant), P0 (without phosphorus), P1 (7 Kg fed^{-1} or 25 ppm P), P2 (10 Kg fed^{-1} or 50 ppm P), P3 (13 Kg fed^{-1} or 100 ppm P), Si0 (without Nano- silica), Si1 (2 mM SiO$_2$), Si2 (4 mMSiO$_2$), AT (Application techniques)

(Lavinskya et al., 2016). Similarly, silicon enhances the absorption of water and nutrients such as phosphorus (P) and potassium (K), boosts the rate of chlorophyll biosynthesis and photosynthesis efficiency, increases the activity of antioxidant enzymes, alters the hormone balance in plants, and raises protein levels, according to Hassan et al. (2019). Our results corroborate those of Saudy et al. (2023), who found that the application of Si had a substantial impact on the grain yield, straw, and biological characteristics of wheat grown on calcareous soil. Furthermore, foliar application of nano silicon has been shown to improve growth and production, particularly at higher concentrations (Elekhtyar, 2016). Besides that, Elekhtyar and AL-Huqail (2023) found that small amounts of silicon used as nano scale fertilizers had advantages that were on par with or even greater than those of large amounts of mineral fertilizer. According to Ranjbar et al. (2019), the application of silicon had a substantial impact on the dry weights of the roots and shoots in calcareous soil. Given that silicon helps plants produce biomass by increasing the accessibility of other elements and reducing nutritional deficiencies, these results make sense (Ahmed et al., 2013).

Moreover, results in Table 2 demonstrate that, under two applications technique, the growth parameters of maize and wheat significantly rose as P rates increased. The greatest average values of wheat (biological, straw, and grain yield) were achieved by P3, which recorded 11117, 7741, and 3375 kg fed^{-1}, respectively. The corresponding results for maize (biological, stover, and grain) production remained high, with average values of 14107, 9830, and 3854 Kg fed-1, respectively. This increase may be explained by the fact that phosphorus is essential for all of the major functions of plants, including respiration, energy transmission, photosynthesis, signal transduction, and the production of macromolecules. Our findings are in excellent accord with those of Rafiullah et al. (2021), who found that higher foliar and soil P concentrations significantly boosted plant height in both maize and wheat. This increase may be due to the crucial role of phosphorus (P) in maintaining vacuolar phosphate (Pi) reserves, which helps create a favorable environment for auxins, supports cell turgor, and aids conservation (Talbi et al., 2015). Since P is a component of phospholipids, its high availability would enhance cell proliferation and membrane formation. On top of that, foliar P treatments were observed to delay leaf senescence and boost wheat grain yields, according to Izhar Shafi et al. (2020).

As far as the application technique is concerned, Table 2 indicates that the average values of foliar application on mature plants across all treatments led to an insignificantly increase in plant productivity in comparison to soil application. This was the case irrespective of the treatment. The biological, straw, and grain yields of wheat have increased to 9891, 6845, and 3047 Kg fed-1 (22 Ardeb fed-1), respectively, according to the findings. In contrast, the parameters that are relevant for maize are 12730, 8863, and 3488 Kg fed-1 (23 Ardeb fed-1), respectively. This increase might be because foliar application enables the element to immediately enter the plant's stomata, allowing it to carry out its duties effectively and resulting in a higher yield. Furthermore, it prevents phosphorus and silicon from changing into an inaccessible form in calcareous soil. Our findings are supported by Arif et al. (2006), who noted that foliar spray is a potential method that can boost crop nutrient availability for increased output. They came to the conclusion that half-recommended phosphorus dosages combined with three sprays of nutrient solution on the leaves at various growth stages improved wheat yield and yield components.

Regarding the NSi-P interaction under various application techniques, Table 2 illustrates that the interaction therapies significantly enhanced the growth metrics of wheat and maize crops. The superior treatment is NSi2P3 at FA treatment, which recorded 12460, 8850, and 3610 kg fed^{-1} for biological, straw, and grain yields of wheat, while for maize crops it recorded 15833, 11572, and 4494 kg fed^{-1} for the same parameters, respectively. Our findings are in excellent accord with those of Akca et al. (2023), who discovered that the dry weight of maize and wheat grown on calcareous soil was significantly impacted by the Si x P interaction. Furthermore, by altering the activity of carbonic anhydrase and the production of photosynthetic pigments, nano silica particles raise the photosynthetic rate, according to Mikael et al. (2021). In addition, an increase in nitrogen causes the grain's protein content to rise, which also raises the grain's dry weight (Awad-Allah et al., 2022). Silicon has a major effect on increasing the protein content of plants because it provides them more nutrients like nitrogen (Cuong et al., 2017). Additionally, it is noteworthy that Si promotes the production of ATP, a crucial energy source for P carriers in the plant (Pavlovic et al., 2021), and boosts the efficiency of photosynthesis (Berger et al., 2007) by raising the chlorophyll content (Cao et al., 2015).

3.2 Total Content of Studied Nutrients in Wheat- Maize Crop Systems

3.2.1 The total phosphorus content

Table 3 presents the results regarding the total P content of wheat and maize influenced by different rates of nano silica, phosphorus, application techniques, and their combined in calcareous soil. All treatments considerably elevated the total phosphorus content in both crops compared to the control thereby (NSi0P0). The cultivation of crops on calcareous soil resulted in reduced absorption and buildup of phosphorus in both the grain and straw. Nonetheless, the incorporation of phosphorus and nano silica into wheat and maize mitigated the adverse impacts of calcareous soil. Regarding the impact of nano silica application, the total phosphorus (P) content significantly increased as the rates of nano silica rose. The maximum value was found with NSi2 (4 mM SiO_2), which raised the P total content in wheat straw and grain by 52 and 50% respectively. Similar increases were obtained at the maize crop, which recorded 26 and 30% for stover and grain, respectively. This might be because silicon promotes the development of plant roots, which improves the roots' capacity to take up and move nutrients throughout the plant. Our findings are in excellent accord with the findings reported by Ranjbar et al. (2019), who found that silicon had a mixed effect on root development and that some studies found that it increased root dry weight. The shape of the roots has a significant role in the effective uptake of water, silicon, and other nutrients, which, in turn, helps plants adapt to water and nutrient shortages. Enhanced root weight or length, enlarged root exudates, and an increase in the volume of the root or its absorbing surface can all enhance nutrient intake. Also, Al-rubaie and Abdulkareem (2024) found that silicon presence markedly influenced phosphorus absorption in maize plants, augmenting it by 51% relative to the control treatment and optimizing phosphorus uptake at the maximum silicon dosage. The alteration was attributed to improved root development, augmented phosphorus availability due to silicon addition, and reduced phosphorus binding. Moreover, Kostic et al. (2017) assert that silicon enhances phosphorus absorption via regulating the transport genes responsible for mineral phosphorus uptake. Silicon enhances phosphorus absorption in corn via improving evaporation, nutrient uptake, and the utilization of available moisture. Alternative silicon forms can create carriers in the cell walls of roots, which modulate the apoplasmic pathway and subsequently transport components from the root cell walls to the shoot region (Vaculíková et al., 2016). Likewise, Akca et al. (2023) noted that silicon therapy effectively enhanced the phosphorus content in plants. Also, Rezakhani et al. (2022) observed that the application of Si increased the wheat shoot content of P by 2.3 times when compared to the control treatment. In plants that thrive in calcareous soils, silicon (Si) has the potential to improve phosphorus uptake. Additionally, silicon treatments, especially nano silica, have proven to be effective in increasing the P content of plants, as noted by Taskin et al. (2022).

Table 3. The total phosphorus content in wheat and maize responds to different rates of nano silica and phosphorus applied using two techniques of application in calcareous soil

NSi Rates	P rates	Phosphorus total content (Kg fed^{-1})							
		Wheat				Maize			
		Straw		Grain		Stover		Grain	
		Application techniques							
		SA	FA	SA	FA	SA	FA	SA	FA
NSi0	P0	6.7	7.2	6.7	7.3	10.4	14.5	11.3	11.4
	P1	14.1	13.1	13.5	16.4	14.2	21.5	15.7	15.0
	P2	17.9	17.3	21.1	20.9	18.6	25.0	16.7	17.6
	P3	20.2	20.1	26.5	25.0	28.9	31.6	21.7	21.7
Mean NSi0		14.6		17.2		20.6		16.4	
NSi1	P0	11.0	11.5	13.3	14.1	12.6	17.9	13.8	14.4
	P1	18.3	15.5	20.1	20.4	19.7	22.0	16.7	17.6
	P2	21.0	24.9	27.1	27.1	21.8	26.2	19.7	20.0
	P3	28.4	29.4	28.1	29.7	31.9	32.5	23.2	26.5

NSi Rates	**P rates**	**Phosphorus total content (Kg fed^{-1})**							
		Wheat				**Maize**			
		Straw		**Grain**		**Stover**		**Grain**	
		Application techniques							
		SA	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**
Mean NSi1		20.0		22.5		23.1		19.0	
NSi2	**P0**	12.8	17.9	16.8	16.7	17.6	18.7	15.3	16.6
	P1	18.5	19.2	22.9	25.5	23.6	24.8	19.3	19.2
	P2	23.3	23.5	29.4	29.2	25.9	27.4	21.4	24.6
	P3	31.9	30.4	32.6	33.5	34.0	34.9	27.1	27.2
Mean NSi2		22.2		25.8		25.9		21.3	
Mean AT		18.7	19.2	21.5	22.1	21.6	24.7	18.5	19.3
Mean P	**P0**	11.2		12.5		15.3		13.8	
	P1	16.4		19.8		21.0		17.3	
	P2	21.3		25.8		24.1		20.0	
	P3	26.7		29.2		32.3		24.6	
LSD at 0.05	**NSi**	1.14		1.68		1.63		0.70	
	P	0.73		1.69		1.07		1.00	
	AT	0.54		1.11		1.08		0.83	
	NSi*P*AT	1.88		3.85		3.73		2.87	

SA (Soil application), FA (foliar on the plant), P0 (without phosphorus), P1 (7 Kg fed^{-1} or 25 ppm P), P2 (10 Kg fed^{-1} or 50 ppm P), P3 (13 Kg fed^{-1} or 100 ppm P), Si0 (without Nano- silica), Si1 (2 mM SiO_2), Si2 (4 mMSiO_2), AT (Application techniques)

Furthermore, as P rates increased, the overall P content of P also significantly increased. P3 achieved the greatest mean value, increasing the total phosphorus content of wheat straw from 11.2 to 26.7 kg fed-1 and from 12.5 to 29.2 kg fed-1 for grain. The total phosphorus (P) content for maize rose from 15.3 to 32.3 kg fed^{-1} in stover and from 13.8 to 24.6 kg fed^{-1} in grain. Our results align perfectly with those of Akca et al. (2023), who observed that the phosphorus content in plants increases proportionally with the provided phosphorus dosage, with a more pronounced rise at higher phosphorus supply levels. Moreover, Al-rubaie and Abdulkareem (2024) found that elevated phosphorus levels resulted in a proportional rise in both absorption and leaf phosphorus content. This increase is attributable to the enhanced availability of phosphorus in the soil. Phosphorus absorption is enhanced by increasing the total dry weight of the vegetative section and the phosphorus concentration in the leaves. A study by Akca et al. (2023) revealed that an increase in the content of soil and foliar phosphorus solution significantly enhanced the absorption of wheat and maize.

In addition, our findings indicate that the total phosphorus content in foliar treatment applications exceeded that of soil applications. The addition of the element directly to the soil may result in some loss, as calcareous soil conditions can transform phosphorus from an available form to an unavailable form. This process reduces the amount of phosphorus accessible to plants, impacting its absorption and transfer. Our findings align remarkably well with those of Pandey et al. (2013), who demonstrated that the primary methods by which plants absorb nutrients provided foliarly are through hydrophilic pores in the leaf cuticle and leaf stomata. Mosali et al. (2004) indicate that plant leaves efficiently absorb foliar phosphorus, thereby improving phosphorus absorption. Furthermore, Rafiullah et al. (2021) indicated that enhancing the rate of foliar application significantly elevated the concentration of P in plant tissues. This suggests that plants might be more efficient in absorbing phosphorus through their leaves rather than from the soil.

The interaction between NSi- P is illustrated in Table 3, which shows that the interaction treatments led to a significant increase in the total P content of wheat and maize. The most effective treatment was NSi2P3 at FA treatment. The research assessed the overall phosphorus content in straw or stover, revealing values of 30.4 kg fed-1 for wheat and 34.9 kg fed-1 for maize, in addition to 33.5 kg fed-1 and 27.2 kg fed-1 for wheat and maize grain, respectively. Our findings were in line with those of Al-rubaie and Abdulkareem (2024), who discovered that the phosphorus concentration at the harvest stage is significantly impacted by the association between phosphorus and silicon levels. Phosphorus values are shown to rise when silicon with phosphorus levels increase. Furthermore, El-Leboudi et al. (2019) found that the maximum concentration and total content of P in the roots and shoots of wheat plants was obtained when Si was applied in conjunction with 13 mg P kg^{-1} soil. Si treatment tended to raise the P content in the green leaves, according to Roy et al. (1971). inference from these findings is that Si improved the mobilization of P from tissue with lower metabolic activity to tissue with higher metabolic activity. Beyond that, Si treatment significantly raised the P concentration in shoots, according to Zia et al. (2017). The absorption of P may increase when the concentration of Si in the root media rises. It can be the result of P desorption from soil adsorption sites.

3.2.2 The total Si content

Table 4 demonstrates that the overall silicon (Si) content from straw or stover, as well as the grain yield of both wheat and maize, was markedly elevated in all treatments relative to the control (NSi0P0). The significant increase is attained by elevating the nano silica concentrations, with the most effective level being NSi2 (4 mM SiO_2). the total content of Si increased by 21 and 41 % for wheat straw and grain, respectively. Furthermore, for maize, the overall silicon (Si) content of stover and grain rose by 30% and 22%, respectively. Moreover, the total silicon content significantly escalates with elevated soil and foliar phosphorus applications. P3 attained the highest average, enhancing Si total content for wheat by 71 and 95%; for maize, it increased by 83 and 90% in straw or stover and grain, respectively. Furthermore, our findings demonstrate that the overall rate of Si in foliar treatment applications exceeded that in soil applications. Moreover, these findings indicate the significant impact of interaction treatments on the total silicon content of calcareous soil. The most efficacious therapy was NSi2P3 at FA. The evaluation determined that the total silicon content of straw or stover and grain was 36 and 30 kg fed-1 for wheat and 30.0 and 39.8 kg fed-1 for maize, respectively.

Table 4. The total silicon content in wheat and maize responds to different rates of nano silica and phosphorus applied using two techniques of application in calcareous soil

NSi Rates	**P Rates**	**Silicon total content (Kg fed^{-1})**							
		Wheat				**Maize**			
		Straw		**Grain**		**Stover**		**Grain**	
		Application techniques							
		SA	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**
NSi0	**P0**	16.5	18.0	9.2	10.3	10.8	12.8	15.5	18.3
	P1	19.4	22.8	10.8	16.1	15.2	19.9	21.6	23.4
	P2	25.2	25.8	16.7	19.1	18.1	21.3	27.6	30.0
	P3	26.9	30.9	19.8	25.1	23.3	23.8	33.1	36.5
Mean of NSi0		23.2		15.9		25.7		18.2	
NSi1	**P0**	17.3	19.0	12.7	13.9	13.5	15.2	18.3	22.3
	P1	22.1	22.6	16.5	18.1	17.9	22.0	25.8	26.1
	P2	24.7	28.6	19.1	22.1	20.9	23.2	30.5	32.9
	P3	28.4	33.5	22.9	28.7	26.5	27.5	37.0	36.8
Mean of NSi1		24.5		19.3		28.7		20.8	
NSi2	**P0**	19.4	21.4	15.2	16.8	17.2	18.2	20.0	22.8
	P1	24.4	27.3	19.8	21.9	21.4	22.4	30.3	29.2
	P2	29.4	31.4	23.0	26.4	24.4	26.1	32.9	35.9
	P3	34.3	36.1	26.0	30.0	29.7	30.1	39.7	39.8
Mean of NSi2		28.0		22.4		31.3		23.7	
Mean of AT		24.0	26.4	19.3	20.7	19.9	21.9	27.7	29.5
Mean of P	**P0**	18.6		13.0		19.5		14.6	
	P1	23.1		17.2		26.1		19.8	
	P2	27.5		21.1		31.6		22.3	

NSi Rates	P Rates	Silicon total content (Kg fed^{-1})							
		Wheat				Maize			
		Straw		Grain		Stover		Grain	
		Application techniques							
		SA	FA	SA	FA	SA	FA	SA	FA
	P3	31.7		25.4		37.1		26.8	
LSD at 0.05	NSi	1.23		1.48		1.47		0.69	
	P	1.92		0.92		1.15		0.83	
	AT	0.98		0.82		0.69		0.64	
	NSi*P*AT	3.38		2.85		2.40		2.20	

SA (Soil application), FA (foliar on the plant), P0 (without phosphorus), P1 (7 Kg fed^{-1} or 25 ppm P), P2 (10 Kg fed^{-1} or 50 ppm P), P3 (13 Kg fed^{-1} or 100 ppm P), Si0 (without Nano- silica), Si1 (2 mM SiO_2), Si2 (4 mMSiO_2), AT (Application techniques)

Our findings were consistent with Akca et al. (2023) who finding that the silicon content in maize and wheat increased with higher phosphorus dosages. The reason may be due to phosphorus enhancing the availability of silicon (Al-rubaie and Abdulkareem, 2024). Cherepanov et al. (1994) determined that elevated phosphorus inputs enhance the probability of phosphorus absorption by silicate minerals, resulting in the formation of compounds that solubilize in the soil. The ability of silicon-rich sources to absorb phosphorus leads to forms that are accessible for plant uptake, as elucidated by Matichenkove and Ammosova (1996). In accordance with Ranjbar et al. (2019), the addition of silicon resulted in an increase in the concentration and overall acquisition of silicon in the shoot. Although the increase is less significant compared to the varying levels of silicon nanoparticles, it is still acceptable due to their potential for faster and easier absorption. This increase in silicon concentration in the shoot also led to a corresponding rise in the concentration of silicon in the soil's solution following the application of silicon. All of the wheat efficiency parameters were significantly impacted by silicon treatment. On top of that, nano-Si treatments raised plant Si concentrations, as reported by Akca et al. (2023).

In the study by Ayman et al. (2020), the addition of silicon had a substantial impact at a higher level than the control. By increasing the quantity of silicon that was accessible in the soil, more plants were able to absorb it, and wheat and maize leaves had higher concentrations. Beyond that, when adding silicon, corn can surpass the 10 g kg^{-1} threshold stated by Al-rubaie and Abdulkareem (2024). This suggests that corn can be categorized as a silicon-accumulative plant, and as such, this property can be used to enhance the plant's growth in response to various biotic and abiotic stressors. Moreover, Al-rubaie and Abdulkareem (2024) indicate that the addition of silicon enhanced the silicon concentration in the leaves. This augmentation was noted across all phosphorus concentrations in comparison to the control. Conversely, for the two silicon treatments, the concentration elevated as the phosphorus levels augmented. Previous research by El-Leboudi et al. (2019) indicated that the overall concentration of Si in plants was considerably influenced by the interactions between Si and P treatments. The highest concentration and total content of Si were seen in the roots and shoots of wheat plants when Si was administered with 13 mg P kg^{-1}. Al-Rubaie and Abdulkareem (2024) noted that compounds containing silicon and phosphorus enhanced the concentrations of both elements in the leaves, as these elements typically exhibit analogous behavior. Phosphorus plays a vital role in the synthesis and activation of enzymes that facilitate nutrition absorption and transport.

3.3 Chemical Properties and Availability of P and Si in Calcareous Soil after Harvest

Subsequent to the wheat and maize harvest, the soil was analyzed to determine the impacts of differing rates of nano silica and phosphorus treatment, employing two application techniques, on pH, $CaCO_3$ %, and the availability of silicon and phosphorus in calcareous soil; results are shown in Tables 5 and 6.

3.3.1 Soil pH

Soil pH is one soil characteristic that provides a complete picture of the medium for plant growth. This overview includes trends in nutrient availability, the destiny of additional fertilizers,

Table 5. The pH and $CaCO_3$ percentage of calcareous soil respond to different rates of nano silica and phosphorus applied using different application techniques after the harvest of wheat and maize

NSi rates	P rates	Wheat				Maize			
		pH		$CaCO_3$ %		pH		$CaCO_3$ %	
		Application techniques							
		SA	FA	SA	FA	SA	FA	SA	FA
NSi0	P0	7.75	7.75	21.9	23.5	7.78	7.84	24.1	26.2
	P1	7.69	7.72	19.2	21.6	7.73	7.72	23.5	23.7
	P2	7.64	7.72	18.8	20.8	7.67	7.45	22.7	22.1
	P3	7.61	7.68	17.1	19.7	7.64	7.71	21.1	20.5
Mean of NSi0		7.69		20.3		7.69		23.0	
NSi1	P0	7.74	7.77	21.6	22.1	7.73	7.84	23.3	25.7
	P1	7.72	7.75	17.9	20.7	7.73	7.81	22.1	23.1
	P2	7.71	7.70	17.4	20.2	7.62	7.72	21.9	21.6
	P3	7.67	7.66	16.9	18.0	7.53	7.63	20.8	19.8
Mean of NSi1		7.72		19.4		7.70		22.3	
NSi2	P0	7.72	7.65	21.4	20.5	7.88	7.85	23.2	23.9
	P1	7.75	7.60	15.2	18.3	7.86	7.80	19.9	22.1
	P2	7.68	7.42	14.8	16.8	7.77	7.79	18.5	19.5
	P3	7.63	7.34	13.8	15.0	7.71	7.70	17.2	18.6
Mean of NSi2		7.60		17.0		7.80		20.5	
Mean of AT		7.69	7.65	18.0	20.8	7.72	7.74	21.5	22.2
Mean P	P0	7.73		21.8		7.82		24.5	
	P1	7.70		18.8		7.78		22.4	
	P2	7.64		18.1		7.67		21.1	
	P3	7.60		16.8		7.65		19.7	
LSD at 0.05	NSi	0.04		0.45		0.025		1.06	
	P	0.02		0.61		0.038		0.94	
	AT	0.02		0.41		0.02		0.49	
	NSi*P*AT	0.05		1.41		0.053		1.71	

SA (Soil application), FA (foliar on the plant), P0 (without phosphorus), P1 (7 Kg fed^{-1} or 25 ppm P), P2 (10 Kg fed^{-1} or 50 ppm P), P3 (13 Kg fed^{-1} or 100 ppm P), Si0 (without Nano- silica), Si1 (2 mM SiO_2), Si2 (4 mMSiO_2), AT (Application techniques)

soil aeration, soil mineralogy, and the final weather conditions in the area (Zhao et al., 2011). The findings obtained in Table 5 showed that, in comparison to the original soil pH and control (NSi0P0), the pH values in calcareous soil after all treatments declined marginally. Also, the application of nano silica slightly (nonsignificant) affected the pH of the soil. While when the P rates increased, the soil pH significant declined. P3 had the lowest average, reducing it by 1.7 and 2.1% for wheat and maize, respectively. However, our findings showed that there was no discernible difference between the two treatment techniques, even though the pH of the soil for SA was lower than FA. In reference to the interaction effect, the pH of the soil significant decreased to 7.3 at NSi2P3 in FA treatment following the harvest of wheat plants, but the pH reached 7.7 following the harvest of maize plants. These outcomes could be explained by the use of varying concentrations of phosphoric acid. Our findings are in excellent accord with those of Hashmi et al. (2016), who discovered that a constant modest fluctuation in soil characteristics was caused by an increase in phosphoric acid rates. Phosphoric acid treatment at any rate resulted in either no change in soil pH or a slight change. Prior research by Akhtar et al. (2016) found no negative consequences of P treatment in alkaline calcareous soil. In contrast to the vast mass of the surface soil, the alkaline calcareous soils' greater buffering ability and the addition of a relatively tiny amount of acid may be the cause.

3.3.2 The percentage of $CaCO_3$ in soil

Results in Table 5 show that application of all treatments decreased the percentage of $CaCO_3$

in calcareous soil after harvesting wheat and maize plants. The $CaCO_3$% significant decreased with increasing nano silica rates. The lowest average was achieved by NSi2 treatment, which decreased $CaCO_3$ by 16 and 11% for wheat and maize, respectively. Also, soil $CaCO_3$% significant decreased by increasing P with the lowest value by P3 application by 23 and 19 % for wheat and maize respectively. Furthermore, our results demonstrated that the two application techniques differed. After the treatments were applied to the soil (SA), the percentage of $CaCO_3$ was lower than the percentage after the treatments were applied to the plant (FA).This could be because adding phosphoric acid, which is a strong acid, to calcareous soil causes the calcium carbonate to dissolve, reducing the quantity of $CaCO_3$. Along with lowering the soil's pH and $CaCO_3$, the carbon dioxide and other chemicals created by this reaction may also make phosphorus more soluble in the soil. Additionally, calcium silicate slightly soluble salts are created when nano silica combines with calcium. Regarding the interaction treatments, soil $CaCO_3$% significant decreased to 13.8% at the NSi2P3 at SA treatment, in contrast to the NSi0P0 at fA treatment, which noted 23.5% after the wheat crop harvest. After the maize harvest, the percentage significant decrease of $CaCO_3$ in treatment NSi2P3 at SA was 17.2% compared to 26.2% in treatment NSi0P0 at FA application. Our findings are in excellent accord with the results published by Gharaibeh et al. (2010), who reported that adding phosphoric acid to calcareous soil causes it to react with the free lime in the soil to generate the insoluble dicalcium phosphate. Nevertheless, further research is necessary to understand the impact of nano silica on the calcium carbonate concentration of calcareous soil.

3.3.3 Soil availability of silicon and phosphorus

Table 6 demonstrates that, under calcareous soil conditions, the application of all examined treatments enhanced the accessible quantity of P and Si in comparison to CR treatments. Additionally, as the nano silica rate increased, the accessible amounts of P and Si also significant increased, with NSi2 demonstrating the highest values in both soil application (SA) and foliar application (FA). The availability of P rose by 7 and 24% for wheat and maize, respectively. While the availability of Si increased by 11 and 5% for wheat and maize, respectively. likewise, the availability of the nutrients under study significant rose as the rates of P administration increased; the usage of P3 produced the highest value. This resulted in an increase in P availability, with increases of 37 and 29% for wheat and maize, respectively. Also, The rising values for Si availability, 19 and 16% for wheat and maize, respectively. When it came to the availability of nutrients, soil treatment was often superior to foliar treatment. This might be the result of adding treatments that decreased the pH (up to 7.3) and calcium carbonate content (up to 13 % of the soil), increasing the accessible amount of the two nutrients, silicon and phosphorus, in the calcareous soil. Additionally, each treatment had a beneficial effect on the adsorption and release of the other. Furthermore, the interplay among the examined treatments improved the P and Si availability in the calcareous soil.

Table 6. Response of phosphorus and silicon availability of calcareous soil to varied rates of phosphorus and/or nano silica at two application methods after harvested wheat and maize

NSi Rates	P rates	Available nutrients mg Kg^{-1}							
		Wheat				Maize			
		phosphorus		silicon		Phosphorus		silicon	
		Application techniques							
		SA	FA	SA	FA	SA	FA	SA	FA
NSi0	P0	15.1	16.0	95	92	19.6	17.7	92	93
	P1	19.3	17.5	106	95	23.1	19.9	98	97
	P2	20.0	19.5	115	104	25.3	20.1	104	104
	P3	22.3	22.5	120	111	26.7	22.5	109	110
Mean NSi0		19.0		105		21.9		101	
NSi1	P0	16.2	18.1	103	98	24.6	18.8	96	96
	P1	19.8	18.6	107	99	25.7	21.0	104	101
	P2	21.3	18.9	114	103	28.5	23.4	106	106
	P3	22.4	23.5	125	113	30.2	24.4	112	111
Mean NSi1		19.8		108		24.6		104	

NSi Rates	**P rates**	**Available nutrients mg Kg^{-1}**							
		Wheat				**Maize**			
		phosphorus		**silicon**		**Phosphorus**		**silicon**	
		Application techniques							
		SA	**FA**	**SA**	**FA**	**SA**	**FA**	**SA**	**FA**
NSi2	**P0**	18.6	16.6	110	107	25.9	21.8	103	97
	P1	19.9	18.4	116	109	27.4	23.6	105	103
	P2	20.9	21.7	122	112	29.1	26.7	106	106
	P3	23.0	24.1	138	116	31.1	30.5	112	116
Mean NSi2		20.4		116		27.0		106	
Mean AT		19.9	19.60	114	105	26.4	22.5	104	103
Mean P	**P0**	16.8		101		21.4		96	
	P1	18.9		105		23.4		101	
	P2	20.4		112		25.5		106	
	P3	23.0		121		27.6		112	
LSD at 0.05	**NSi**	0.39		2.06		0.66		1.53	
	P	0.90		1.59		0.61		1.20	
	AT	0.46		1.47		0.38		0.90	
	NSi*P*AT	1..60		5.09		1.31		3.10	

SA (Soil application), FA (foliar on the plant), P0 (without phosphorus), P1 (7 Kg fed^{-1} or 25 ppm P), P2 (10 Kg fed^{-1} or 50 ppm P), P3 (13 Kg fed^{-1} or 100 ppm P), Si0 (without Nano- silica), Si1 (2 mM SiO_2), Si2 (4 mMSiO_2), AT (Application techniques)

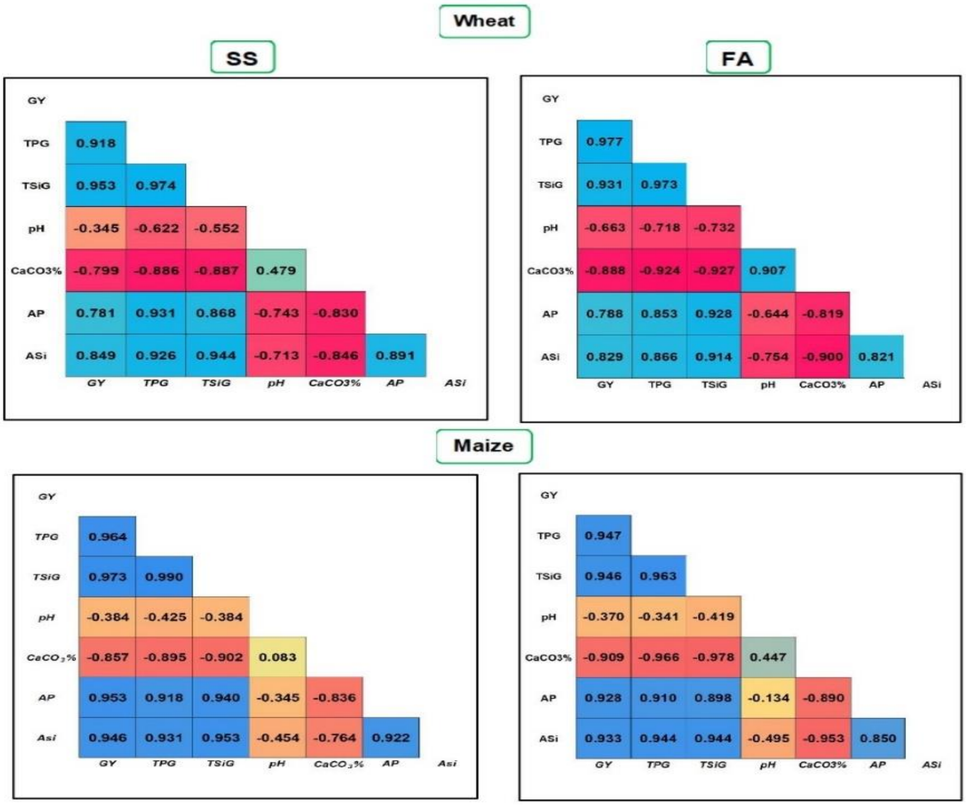
Our results are in good agreement with those of Brady and Weil (1999), who reported that the high levels of calcium and magnesium associated with carbonates reduce the availability of phosphorus. Phosphorus availability in calcareous soils is usually restricted. Maximum availability to plants of both native and applied P is in the pH range of 6.0–7.5. At higher pH values, phosphate anions react with Ca and Mg to form phosphate compounds of limited solubility. As demonstrated by Cherepanov et al. (1994), who discovered that applying phosphorus at high doses boosts the possibility of its absorbing on silicate minerals, forming compounds that dissolve in the soil, Al-rubaie and Abdulkareem (2024) stated that the accessible quantity of P and Si rose with increasing P applied levels. Matichenkove and Ammosova (1996) discovered that sources high in silicon may absorb phosphorus, making it accessible to plants, which in turn causes plant absorption. Likewise, Rafiullah et al. (2021) indicated that both foliar and soil treatment had positive outcomes by boosting crop growth and NPK accessibility. Increasing the amount of phosphorus in the soil by foliar application may improve phosphorus utilization efficiency and lessen crop dependence on soil phosphorus. The addition of P fertilizer and foliar spray revealed a considerable phosphorus concentration in the soil during the wheat harvest. Acka et al. (2023) also discovered that as the P supply increased, the concentration of plant-available P in soils after both maize and wheat cultivation rose.

In accordance with Elekhtyar and AL-Huqail (2023), Si can increase and enhance phosphorus (P) availability. Therefore, by reducing the accessible amount of Fe and Mn in plants, Si can indirectly improve P accessibility (Lux et al., 2003). Furthermore, Al-rubaie and Abdulkareem (2024) found that silicon increases the amount of phosphorus in the soil, ensuring that plants may access it in enough amounts. Furthermore, silicon increases the effectiveness of nutrient utilization and influences how nutrients bond to soil particles, allowing the plant to access them (Koski-Vähälä et al., 2001). Furthermore, silicon enhanced phosphorus availability in several ways. For example, silicates alter the acidity of soil, which in turn improves phosphorus availability by dislodging adsorbed phosphorus into the soil's solution (Neu et al., 2017). Additionally, silicate complexes in both inorganic and organic forms are the soil's mobile forms of silicon that substitute the phosphorus found in calcium phosphate, helping to transform unavailable phosphorus into phosphorus that plants can use (Matichenkove & Ammosova, 1996). In the work of Hömberg et al. (2020), the concentration of phosphorus and silica in the soil solution determines the competition between the two elements. Regarding the biological component, silicon's addition enhances the activity of functional microorganisms in soil, particularly P-solubilizing bacteria, by raising basic ions, enhancing soil pH, speeding up organic matter breakdown and phosphorus mineralization, and forming soil structure.

On the other hand, Akca et al. (2023) found that in both wheat and maize soils, the Nano-Si and Na-Si treatments raised plant-available Si concentrations, which in turn raised plant Si concentrations. Furthermore, Zhu et al. (2024) reported that the available silicon, potassium, and phosphorus within the soils treated with nano silicon fertilizer were significantly higher than those in the CR and the soil enzyme activity of the treatments with nano silicon fertilizer was significantly higher than that of the CR. So, applying nano silica fertilizer is crucial for increasing microbial diversity, soil enzyme activity, and soil nutrients. Furthermore, it was noted by Taskin et al. (2023) and Gunes et al. (2025) that there are important interactions between soil and plant nutrition for Si and P. Silicon may have an impact on the processes that pertain to plants' absorption of P, including the competing adsorption and release interplay of silicate and phosphate anions (Soratto et al. 2019) and the enhancement of organic acid exudation from roots, which mobilizes P in the rhizosphere (Kostic et al. 2017). P is released into the soil solution when silicate and phosphate anions conflict for similar binding sites, making more P accessible for the plant (Das et al. 2019). Furthermore, many studies indicated that foliar application is a promising technique that can increase the availability of nutrients for crops to obtain higher yields (Rafiullah et al., 2021). Our results indicated that applying phosphorus through a foliar technique may enhance the efficiency of soil-applied phosphorus use and reduce crops' dependency on soil phosphorus. The foliar-applied P could supplement the soil P and may reduce the crop's reliance on it.

3.4 Association between the Traits under Study

Fig. 1 shows the Pearson's correlation coefficients for the seven parameters under study (grain yield, pH, CaCO$_3$, soil availability of



	GY	TPG	TSiG	pH	CaCO3%	AP	ASi
GY							
TPG	0.918						
TSiG	0.953	0.974					
pH	-0.345	-0.622	-0.552				
CaCO3%	-0.799	-0.886	-0.887	0.479			
AP	0.781	0.931	0.868	-0.743	-0.830		
ASi	0.849	0.926	0.944	-0.713	-0.846	0.891	

	GY	TPG	TSiG	pH	CaCO3%	AP	ASi
GY							
TPG	0.977						
TSiG	0.931	0.973					
pH	-0.663	-0.718	-0.732				
CaCO3%	-0.888	-0.924	-0.927	0.907			
AP	0.788	0.853	0.928	-0.644	-0.819		
ASi	0.829	0.866	0.914	-0.754	-0.900	0.821	

	GY	TPG	TSiG	pH	CaCO$_3$%	AP	Asi
GY							
TPG	0.964						
TSiG	0.973	0.990					
pH	-0.384	-0.425	-0.384				
CaCO$_3$%	-0.857	-0.895	-0.902	0.083			
AP	0.953	0.918	0.940	-0.345	-0.836		
Asi	0.946	0.931	0.953	-0.454	-0.764	0.922	

	GY	TPG	TSiG	pH	CaCO3%	AP	ASi
GY							
TPG	0.947						
TSiG	0.946	0.963					
pH	-0.370	-0.341	-0.419				
CaCO3%	-0.909	-0.966	-0.978	0.447			
AP	0.928	0.910	0.898	-0.134	-0.890		
ASi	0.933	0.944	0.944	-0.495	-0.953	0.850	

Fig. 1. Coefficients of correlation among the variables being examined as influenced by different phosphorus and nano silica rates at two application methods following the harvest of maize and wheat

SS (Soil application), FA (foliar on the plant), GY (Grain yield), TPG (Grain total P content), TSiG (Grain total Si content), AP (Available P), ASi (Available Si)

P and Si, and grain total content of P and Si) under varying phosphorus and nano silica rates at two application ways after maize and wheat harvest in calcareous soil. The results showed strong positive relationships between GY and TPG, TSiG, OM%, AP, and ASi. However, there were significant negative relationships between GY, pH, and $CaCO_3$ percentages. Additionally, there was a high positive association between AP and ASi (R^2 = 0.89 and 0.82 for wheat) as well as 0.92 and 0.85 for maize at SS and FA, respectively). They showed negative results for AP, ASi, pH, and the percentage of $CaCO_3$. Regarding the relationships between the various trait categories, TPG, ASi, and TSiG showed significantly positive connections after harvesting wheat and maize. Our findings are consistent with the results reported by Elekhtyar and AL-Huqail (2023), who found that silicon application and Si enhanced phosphate absorption in rice, which is directly related to higher growth and yield. Si can also increase and enhance the availability of P. Si can therefore indirectly increase the accessibility of P. Along with a predicted positive relationship between plant-available Si of wheat rhizosphere soil and plant growth and P availability, Rezakhani et al. (2022) discovered a significant and positive relationship between adsorbed Si of wheat rhizosphere soil and the shoot uptake of Si (r^2 = 0.84), as well as the shoot uptake of P (r^2 = 0.58). Al-Rubaie and Abdulkareem (2024) demonstrated the strong relationship between plant phosphorus metabolism and silicon accumulation, suggesting that the high solubility of silicon in soil causes phosphorus to become saturated in soil pore water and plant tissues by increasing its availability.

4. CONCLUSION

Several fixation activities take place in calcareous soils when phosphorus fertilizer is applied, which progressively decreases the fertilizer's solubility and plant availability. Furthermore, continuous plant production and phosphorus fertilization cause the soil's silicon availability to decline, necessitating the exploration of alternative silicon fertilizers, such as nano silica, which is more effective in plants and soil. The findings recorded a significant increase in wheat and maize plant growth parameters and the total content of Si and P in both crops. As well as, soil properties including pH, $CaCO_3$, and the availability of phosphorus (P) and silicon (Si), were also affected by the application of NSi and P using different application techniques, such as soil and foliar application, and their combination. The most effective treatment was NSi2P3 with foliar application, which recorded a grain yield production of 3.6 ton fed-1 for wheat and 4.5 ton fed-1 for maize. Remarkably, foliar applications of the treatments demonstrated comparable or superior effectiveness compared to soil treatment applications, with wheat and maize grain yield production reaching 3047 (22 Ardeb fed-1) and 3488 Kg fed-1 (23 Ardeb fed-1), respectively. Additionally, these results demonstrated that wheat plants outperformed maize plants in terms of response. The results also showed that there was slightly difference between application of NSi2P2 and NSi2P3 on the plant productivity, which makes it possible to reduce the amount of phosphorus fertiliser applied to the plants under the same experimental conditions. Applying nano silica at a rate of 4 mmol SiO_2 or more helps make phosphorus more available, increasing its absorption and transport by plants, which in turn helps increase productivity. Also, using nano silica made from agricultural waste might help cut expenses by reducing the quantity of phosphate fertilizers required in calcareous soils and decrease the environmental pollution by reducing the use of chemicals in agriculture. Finally, we can recommend using foliar application of nano silica with P at the rate of 4 mM SiO_2 and 100 mg P L^{-1} for cultivating wheat and maize in the calcareous soils of the Nubaria region.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

This work's creators attest that no generative AI techniques, such as text-to-text generators or large language models (Chat GPT, COPILOT, etc.), were used in its creation or modification.

ACKNOWLEDGEMENTS

The authors would like to thank the Development of Soil Conditioners Project, Department of Physics and Chemistry of Soil in Soils, Water and Environ. Res. Inst., Agric. Res. Centre (ARC), Giza, Egypt, for providing all the facilities required to complete this study.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/144817