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RESEARCH ARTICLE

Silicon application timing on phosphorus availability and fractionation in tropical soil and its effects on maize growth

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Abstract

Background and Aims Phosphorus (P) is a limiting nutrient for agricultural production in tropical soils due to its adsorption onto Fe and Al oxides. Silicon (Si) also exhibits affinity for these compounds and can displace P into the soil solution. Studies evaluating application timing to increase P availability remain scarce. This study evaluated the effect of Si and P application timing on soil P availability and maize growth.

Methods The experiment was conducted in a greenhouse using a randomized block design with four replicates. Six treatments were evaluated: Control (without P and Si); P applied at sowing (100 mg kg^{-1}); Si applied at sowing (480 mg kg^{-1}); P applied 30 days before sowing + Si at sowing; Si applied 30 days before sowing + P at sowing; and P + Si applied together at sowing. At 60 days of maize cultivation; physiological parameters, biomass, P and Si concentration and uptake, and soil P fractionation were evaluated.

Results The results demonstrated that Si applied 30 days before sowing + P at sowing, or P + Si applied together at sowing, increased available P in soil. The P + Si combination, regardless of the application timing, did not increase P concentration and uptake in maize plants.

Conclusion The application of Si before P, or the joint application of P and Si, can be an alternative to increase available P levels in tropical soil, however, no influence of the timing of P and Si application was observed on maize growth.

Keywords Weathered soil · Silicate fertilization · Adsorption competition · Soil fertility management

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Introduction

Phosphorus (P) is a vital nutrient for plant development, playing a key role in processes such as cellular respiration and the synthesis of fundamental molecules, including nucleic acids and phospholipids (Lambers 2022; Iqbal et al. 2023). In tropical soils, P availability is reduced due to intense weathering, which results in the predominance of 1:1 clay minerals, such as kaolinite, along with iron (Fe_2O_3) and aluminum (Al_2O_3) oxides (Vitousek et al. 2010). These oxides have a strong interaction with phosphate, increasing P retention through adsorption and the formation of low-solubility complexes (Zhong et al. 2025).

As a result, the efficiency of phosphate fertilizers is limited; literature reports that only 20% of the phosphorus applied via fertilizers is effectively utilized by plants in the first year (Mazlouzi et al. 2020). This often makes P a limiting nutrient for plant growth due to its low availability in the soil solution (Zeng et al. 2022). Furthermore, the primary source of P used in agriculture is phosphate rock, a non-renewable resource with finite reserves that could be depleted within the next 200 years (Van Vuuren et al. 2010). Given this problem, increasing phosphorus use efficiently by plants is one of the greatest challenges in tropical agriculture, making the development of strategies to reduce its adsorption fundamental.

Studies have demonstrated that silicon (Si) application has the potential to increase phosphorus (P) availability in soil (Prado and Fernandes 2001; Araújo et al. 2022; Pavlovic et al. 2021; Jinger et al. 2022; Uhuegbue et al. 2024). Evidence on the improvement of Si-mediated P availability began to be reported in 1905, and today it is still a topic that needs to be further explored, this was discussed in a recently published article that presented a compilation of data on how the application of P and Si can increase P uptake by crops (see, Mückschel et al. 2025). Two mechanisms have been proposed to explain this effect: the first is related to the competition between silicate and phosphate anions for the same adsorption sites in the soil, which reduces P fixation and increases its availability (Carvalho et al. 2001; Sandim et al. 2014). A study conducted with 143 Arctic soils demonstrated that increased Si availability promoted P desorption, favoring the mobilization of iron-associated P on mineral surfaces (Schaller et al. 2019). The second mechanism involves the indirect effect of Si sources on soil pH, promoting an increase in OH^- ion concentration and favoring the precipitation of Fe and Al. This process reduces the interaction of phosphate with oxide surfaces, decreasing its fixation and increasing its availability to plants (Smyth and Sanchez 1980; Ma and Takahashi 1990; Deus et al. 2020; Gunnarsen et al. 2022), this occurs because under pH conditions > 6.0 the adsorption of Si is intensified and consequently the P is released into the soil solution (Haynes and Zhou 2020). Although the mechanisms mentioned above are the most widely explored, the literature also reports that these effects of Si on increasing P availability are additionally related to Si precipitation on mineral surfaces, greater stability of the Si–O chemical bond, or enhanced development of the Si-mediated root system (Mückschel et al. 2025). However, these proposed mechanisms still require further study.

Despite evidence that Si can increase soil P availability and, consequently, its uptake by plants, the optimal application strategy to maximize this effect remains unclear. Some studies utilizing calcium and magnesium silicates as Si sources typically apply them before phosphate fertilization, as these products are also used for soil pH correction (e.g., Castro et al. 2016; Deus et al. 2020; Silva et al. 2025). Silicon is also supplied with P at the time of sowing (Wang et al. 2020); furthermore, studies have compared Si application methods in two soils cultivated with maize to enhance nutrient uptake (da Silva et al. 2023). However, there is a lack of studies comparing the optimal timing of Si application aimed at increasing soil P availability and plant development.

It is hypothesized that Si application prior to phosphate fertilization can increase P availability in soil and consequently the absorption of this nutrient for the plants, as Si can occupy phosphate adsorption sites, thereby preventing rapid P adsorption. In this context, to address this knowledge gap, this study aimed to evaluate the effect of Si and P application timing on soil P availability, as well as its effects on maize P uptake and development in tropical soil.

Materials and methods

Experimental design, treatments, and soil characterization

The experiment was conducted in a plastic tunnel without temperature control at the Department of Forest Science, Soils, and Environment of the School

of Agriculture (FCA/UNESP), Botucatu campus, SP, Brazil. A randomized block design was used, consisting of six treatments with four replicates, totaling 24 experimental units:

1. Control: without P and Si application;
2. Control (P_s): 100 mg kg^{-1} of P applied at sowing;
3. Control (Si_S): 480 mg kg^{-1} of Si applied at sowing;
4. $P_b + Si_s$: 100 mg $kg^{-1}$of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s);
5. $Si_b + P_s$: 480 mg kg^{-1} of Si applied 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing;
6. $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si applied together at sowing.

The soil used was classified as an Ustox (USDA 1999), with a clayey texture, no prior agricultural management, and low P content. Before setting up the experiment, chemical and particle-size characterizations of the soil were performed (Table 1).

Table 1 Chemical and particle-size characterization of the soil before conducting experiment

Property	Unit	Value
pH ($CaCl_2$)(1)	–	4.3
Organic matter(1)	g kg^{-1}	22.11
Available P (resin) (1)	mg kg^{-1}	6.32
Exchangeable Al^{3+}(1)	mmolc kg^{-1}	7.37
Potential acidity (H + Al) (1)	mmolc kg^{-1}	62.11
Exchangeable K(1)	mmolc kg^{-1}	0.84
Exchangeable Ca(1)	mmolc kg^{-1}	11.58
Exchangeable Mg(1)	mmolc kg^{-1}	2.11
Sum of bases(1)	mmolc kg^{-1}	14.74
Cation exchange capacity (CEC)(1)	mmolc kg^{-1}	76.84
Base saturation (V) (1)	%	19
Available S(1)	mg kg^{-1}	56.84
Available Si ($CaCl_2$)(3)	mg kg^{-1}	7.6
B(1)	mg kg^{-1}	0.26
Cu(1)	mg kg^{-1}	6.00
Fe(1)	mg kg^{-1}	16.84
Mn(1)	mg kg^{-1}	3.68
Zn (1)	mg kg^{-1}	0.21
Sand (2)	%	18.8
Silt (2)	%	22.5
Clay(2)	%	58.7
SiO_2 (4)	g kg^{-1}	26.96
Al_2O_3 (4)	g kg^{-1}	106.73
MnO (4)	g kg^{-1}	2.14
Fe_2O_3 (4)	g kg^{-1}	42.75

Methodology: Raij et al. (2001) (1), Claessen (1997) (2), Korndörfer et al. (2004) (3) and Teixeira et al. (2017) (4)

Experimental setup and management

The experiment was conducted using plastic pots (height 35 cm; top diameter 36 cm; bottom diameter 25 cm) containing 15 kg of soil. Dolomitic limestone (Relative Neutralizing value = 95%) was incorporated into each experimental unit to increase base saturation to 70%, as recommended for maize (Cantarella et al. 2022). Subsequently, the soil was incubated for 30 days at approximately 70% of its field capacity. After the incubation period, the soil was air-dried before receiving the treatments described above. Triple superphosphate (20% total P) was used as the P source, and hydrophilic fumed silica was used as the Si source (Aerosil 300®, Evonik Operations GmbH, Germany; specific surface area 270–330 m^2 g^{-1}, 25% soluble Si). After the limestone incubation period, the soil was air-dried. P and Si, in granule and powder form, respectively, were incorporated into the entire soil volume of each pot according to the treatments described in topic 2.1. After the incorporation of the treatments "before sowing" (treatments: 4 and 5), all experimental units were again incubated for a period of 30 days.

After period of 30 days, on the sowing day, the other treatments were incorporated, in addition, all experimental units received 120 mg kg^{-1} of N, 120 mg kg^{-1} of K and 20 mg kg^{-1} of Zn, using urea, potassium chloride (KCl), and zinc chloride ($ZnCl_2$) as sources, respectively. Nitrogen and K fertilization were split into three applications: 33.33% at sowing, and the remainder at 15 and 30 days after emergence.

Five seeds of hybrid maize (cv. Top-cross BRS 2107, link) were sown per experimental unit; seeds were treated with a pesticide based on pyraclostrobin + thiophanate-methyl and fipronil. At seven days of seedling emergence, thinning was carried out maintaining two plants per experimental unit. Throughout the experiment, soil moisture was maintained at approximately 70% of field capacity. A product based on Thiamethoxam + Lambda-cyhalothrin was used for pest control, and Mancozeb were used for fungal disease control was used once during the

entire conduct of the experiment. All plant and soil evaluations were performed 60 days after sowing.

Analyzed variables

Plant evaluations

Plant height *Plant height (cm)* was measured from the soil surface to the plant apex using a tape measure. For this variable, the average of two plants per experimental unit was considered.

Physiological analyses At the tasseling stage (VT), leaf gas exchange was measured using a portable infrared gas analyzer (IRGA, LI-6400XT, Li-Cor, Lincoln, Nebraska, USA). During measurements, the equipment was set to 2000 µmol of photons m^{-2} s^{-1} of Photosynthetically Active Radiation (PAR) and relative humidity between 50% and 60%. The following parameters were obtained: photosynthetic rate (*A*), internal CO_2 concentration (Ci), stomatal conductance to water vapor (g_s), and transpiration rate (*E*). Readings were taken between 9:00 and 11:00 AM.

Shoot dry mass To determine shoot dry mass, one plant per pot was cut at ground level, washed with distilled water, placed in paper bags, and dried in a forced-air oven at 65 °C until reaching a constant weight. Weight was recorded using a semi-analytical balance.

P and Si content and uptake in shoots Shoot samples were ground in a Wiley mill to determine P and Si concentrations. P concentration was measured according to Malavolta et al. (1997), using nitric-perchloric digestion and quantification via the molybdenum blue colorimetric method. Silicon (Si) was determined by autoclave digestion and quantified by colorimetry using the molybdovanadate (yellow) method (Elliott and Snyder 1991). The uptake of P and Si was calculated by multiplying the element concentration in the tissue by the dry mass weight.

Soil evaluations

Plant available soil P and Si Available P was extracted using the anion exchange resin method (Raij et al. 2001) and quantified by colorimetry via the molybdenum blue method (Murphy and Riley 1962). Available Si was extracted with 0.01 mol L^{-1} $CaCl_2$, and the concentration was measured using the molybdenum blue colorimetric method (Korndörfer et al. 2004).

Soil P fractionation The P fractionation was performed using the method of Hedley et al. (1982) with modifications (Condron et al. 1985; Gatiboni and Condron 2021), which consisted of sequentially extracting different forms of P according to their solubility and availability to plants. The available P (P_{M3}) considered labile was obtained from a 0.5 g soil sample in Mehlich-3 extracting solution; subsequently, labile P forms were obtained from the residual soil content after obtaining P_{M3}. The inorganic P bound to Fe and Al (Pi_{NaOH}) was obtained with 0.5 mol L^{-1} NaOH extracting solution; sequentially, inorganic P bound to calcium (P_{HCl}) was obtained with 1 mol L^{-1} HCl extracting solution. With a 2 ml aliquot of the extract obtained from the Pi_{NaOH} extraction, 2 ml of H_2SO_4 + 0.75 g of $(NH_4)_2S_2O_8$ were added for $P_{autoclave}$ (Total P in extract) quantification, for subsequent quantification of organic P (Po_{NaOH}). Po was determined by subtraction between $P_{autoclave}$ and Pi_{NaOH}. $P_{ccluded}$ (fraction of P not quantified by the extraction methods used) was also estimated, obtained by the difference between total P extracted by $H_2SO_4 + H_2O_2$ and the extracted forms of P (Gatiboni and Condron 2021). The reading of the extracts was performed by colorimetry using the method of Murphy and Riley (1962), except for Po which followed the method described by Dick and Tabatabai (1977).

Fe and Al were also quantified from the Mehlich-3 extract in the Inductively Coupled Plasma (ICP), to determine the P sorption saturation, as shown in the equation below (Sharpley et al. 2007).

$$P_{Sat}(\%) = \frac{P_{M3}}{Fe_{M3} + Al_{M3}} x100 \quad (1)$$

where:

$P_{sat}(\%)$ P sorption saturation
P_{M3} P extracted by Mehlich-3
Al_{M3} Al extracted by Mehlich-3
Fe_{M3} Fe extracted by Mehlich-3

Statistical analysis

Data were tested for homoscedasticity and normality and then subjected to analysis of variance (ANOVA). When significant, means were compared using the Tukey test ($p < 0.05$) with the *ExpDes.pt* package (Ferreira et al. 2018). Multivariate relationships between treatments and soil–plant variables were explored via Principal Component Analysis (PCA). For detailed analysis, data were divided into three groups: (i) plant parameters (Plant height, shoot dry biomass, P and Si concentration and uptake); (ii) physiological parameters (A, g_s, C_i and E); and (iii) soil parameters (available P—M3, Pi_{NaOH}, Po_{NaOH}, Pi_{HCl}, Occluded P, and available Si). Rather than corresponding to individual measured parameters, the Principal Components (PC1 and PC2) were established as linear combinations of all variables, serving as orthogonal axes that extract the maximum variance within each dataset. Due to different units of measurement, data were previously standardized to unit variance (Z-score) using the *decostand* function to homogenize scales and calculate the correlation matrix. Ordinations were performed using the vegan package with the *rda()* function (Oksanen et al. 2026). Graphical representations (biplots) and 95% confidence ellipses were generated using the *ggplot2* package (Wickham 2011).

Results

P fractions as a function of the timing of P and Si application

The application of Si before the application of P ($Si_b + P_s$ treatment) and the application at the same time of P and Si ($P_s + Si_s$ treatment) contributed to the highest increment of available P (P extracted by M3), being different from the mean obtained with the conventional application of P (control P_s), the percentage difference of the increment of available P between these treatments was 60.49% and 54.78% for $Si_b + P_s$ and $P_s + Si_s$, respectively. The lowest means were observed in the treatments that did not receive P (Fig. 1a). The inorganic P extracted by NaOH (Pi_{NaOH}) obtained the highest means with the application of the treatments $P_s + Si_s$ and $P_b + Si_s$, however, these means did not differ from the $Si_b + P_s$ combination and the Control P_s treatment. The lowest mean was observed in the control treatment and was not different from the Control Ps or control Sis treatments (Fig. 1b).

The organic P (Po_{NaOH}) presented a higher mean in the control treatment and differed from the treatments control (P_s). The Si control treatment did not show a significant difference compared with the control. (Fig. 1c). The inorganic P extracted by HCl (Pi_{HCl}) (Fig. 1d) and the occluded P (Fig. 1e) did not present a significant difference among the evaluated treatments.

Observing the percentages of each P fraction, it was noted that the treatments that did not receive P, Control and Control (Si_s) presented the lowest percentages of P available for the plant (P M3), being responsible for only 0.19% and 0.14%, respectively. In this fraction, the treatments $Si_b + P_S$ and $P_s + Si_s$ presented the highest percentages of P M3 with 0.86% and 0.84%, respectively. The application of P without Si [control (P_s)] presented a percentage of 0.56% of P. The percentages of Pi_{NaOH} varied between 5.44% to 7.59%. The Po_{NaOH} presented a higher percentage in the control treatment, in this fraction the percentage varied from 2.97% to 6.47%. The variation of Pi_{HCl} was between 0.04% to 0.18%. The percentage of occluded P was 85.61% to 89.53% (Fig. 1f).

Total P, available P resin and available Si in soil

Total P (P extracted by $H_2SO_4 + H_2O_2$) did not present difference as a function of the applied treatments. These contents ranged from 1356.90 to 1600.75 (Fig. 2a). Available P extracted by resin (Fig. 2b) presented higher values than those extracted by Mehlich-3 but presented the same behavior (Fig. 1a).

Available Si in the soil showed a greater increment in the Control Sis and $Si_b + P_s$ treatments, and the lowest means were noted in the treatments that did not receive Si. The application of $P_s + Si_S$ and $P_b + Si_s$ reduced the availability of Si in the soil; this last treatment was also similar to the control and Control P_s (Fig. 2c).

The P saturation percentage in the soil was higher in the treatment that received P and Si at the moment of sowing ($P_s + Si_s$). But this was not different from the $Si_b + P_s$ application. The lowest P saturation indices were observed where P was not

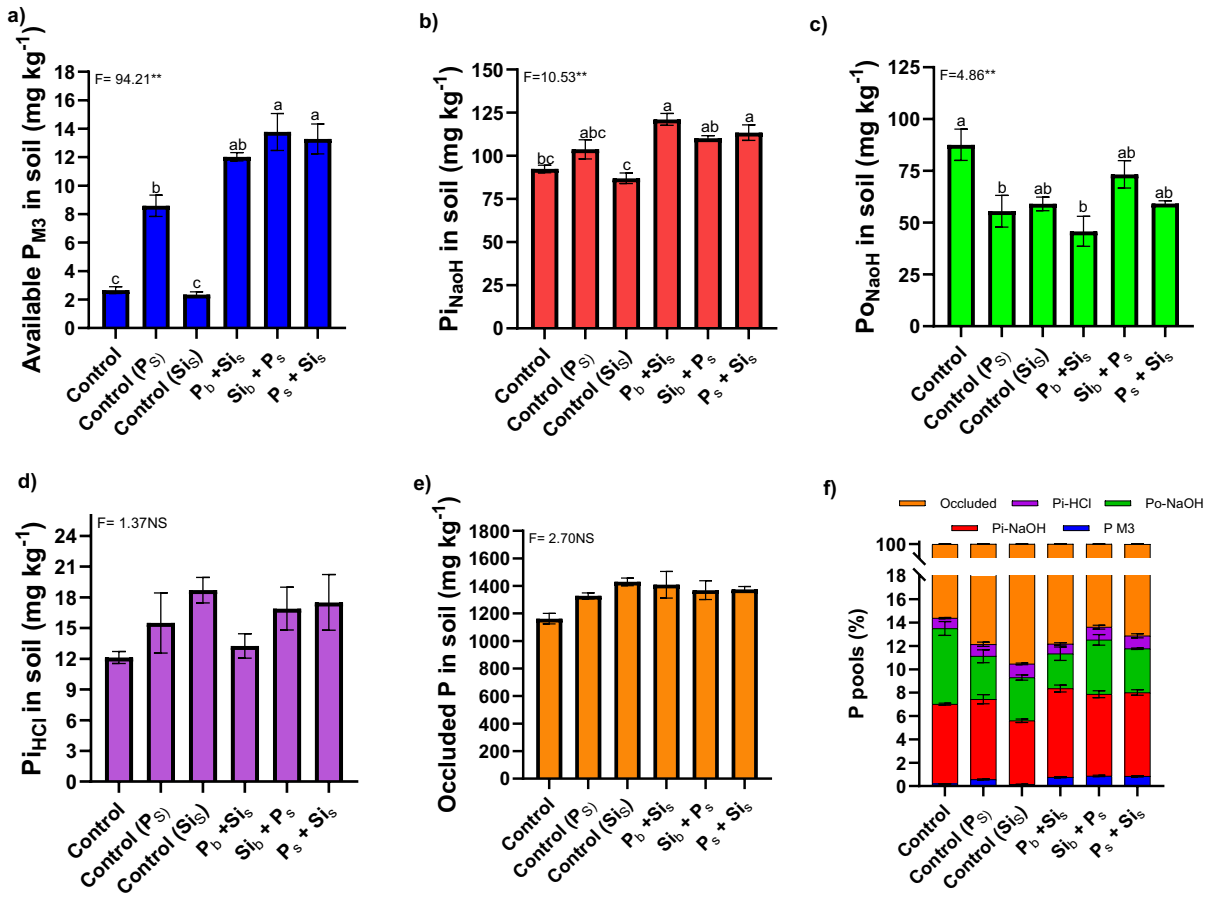


Fig. 1 Available phosphorus (P) extracted by Mehlich-3 (**a**), inorganic P extracted by NaOH (**b**), organic P extracted by NaOH (**c**), inorganic P extracted by HCl (**d**), occluded P (**e**) and percentage of P fractions in the soil (**f**) as a function of applied treatments. Control (P_s): 100 mg kg^{-1} of P applied at sowing; Control (Si_S): 480 mg kg^{-1} of Si applied at sowing; $P_b + Si_s$: 100 mg kg^{-1} of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s); $Si_b + P_s$: 480 mg kg^{-1} of Si added 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing; and $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si added together at sowing. Columns followed by the same letter do not differ from each other by the Tukey test at 5% significance. Error bars represent the standard error (n = 4). ** = Significant at 1%. * = Significant at 5%. NS = No significant

applied. The application only of P (control P_s) presented a difference from the other controls and from the highest means (Fig. 2d).

Physiological analyses

There was a significant difference due to the applied treatments in all evaluated physiological parameters (Fig. 3). The highest photosynthetic rate (*A*) in the shoots of maize plants occurred with the application of P and Si at the time of sowing ($P_s + Si_s$), but it was not different from the individual application of P. The lowest *A* were observed in the treatments that did not receive the application of P (Fig. 3a).

Observing the stomatal conductance (g_s) (Fig. 3b), it was noted that the highest means were obtained with the application of treatments $P_s + Si_s$ and $Si_b + P_s$, but these treatments only differed from the control that received only Si [Control (Si_s)]. The lowest stomatal conductance was observed with the application of Si [Control (Si_s)], but this mean was not different from the control (without application of P and Si) or the control that received only P [Control (P_s)] (Fig. 3b).

The internal carbon concentration (Ci) showed the highest mean with the application of P at sowing [control (P_s)], being different from the control (without application of P or Si), the application of Si

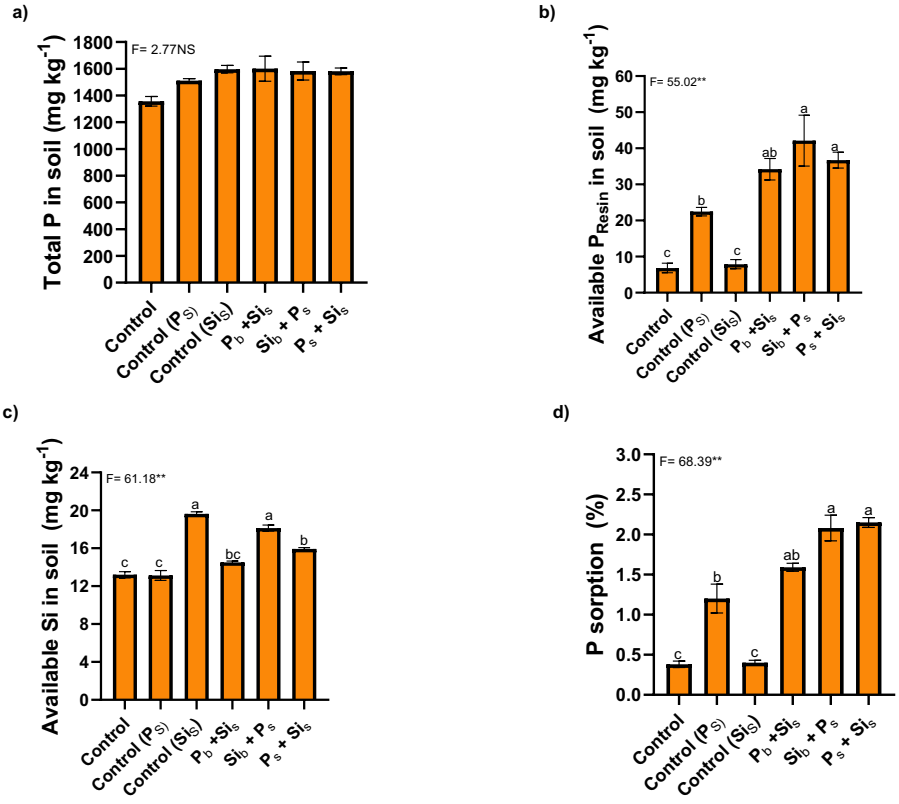


Fig. 2 Total phosphorus (P) (**a**), available P extracted by resin (**b**) and available Si in soil (**c**) and P saturation percentage (**d**) as a function of applied treatments. Control (P_s): 100 mg kg^{-1} of P applied at sowing; Control (Si_S): 480 mg kg^{-1} of Si applied at sowing; $P_b + Si_s$: 100 mg kg^{-1} of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s); $Si_b + P_s$: 480 mg kg^{-1} of Si added 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing; and $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si added together at sowing. Columns followed by the same letter do not differ from each other by the Tukey test at 5% significance. Error bars represent the standard error (n = 4). ** = Significant at 1%. * = Significant at 5%. NS = No significant

[control (Si_S)], and the $Si_b + P_s$ treatment. The lowest mean was obtained with the control treatment (without application of P or Si), and this was not different from the application of Si [control (Si_S)], and the treatments $Si_b + P_s$ and $P_b + Si_s$ (Fig. 3c).

For the transpiration rate (*E*), the highest means were observed with the application of treatments $Si_b + P_s$ and $Si_s + P_s$, which were similar to the treatment that received only P [control (P_s)]. The lowest means were observed in the treatments that did not receive P, and these were different from the highest means (Fig. 3d).

Height, dry mass, concentration, and uptake of P and Si in shoots

The application of P combined with Si or individually, regardless of the timing of application, resulted in increments in the height and shoot dry mass of maize plants. The lowest means were observed in the treatments that did not receive P. An increment in these variables was noted with the application of Si alone compared to the absolute control treatment (Fig. 4a and b).

The Si concentration in the shoot was higher in the treatment that received only Si [Control (Si_s)], and the lowest means were noted in the control and [Control (P_s)], which did not differ from the combined applications $P_b + Si_s$ and $P_s + Si_s$ (Fig. 4c). A greater accumulation of Si was noted when P was supplied, regardless of the timing of P or Si application, this is probably due to the increment in shoot biomass. The individual application of Si showed a higher accumulation than the absolute control treatment (Fig. 4d).

Regarding the P content in the shoot, the greatest increments in this variable were observed in the treatments that received P; these means were higher than the application of Si alone (Control Si_s) and the absolute control. The lowest P contents were verified when there was no application of P (Fig. 4e). The P accumulation in the shoot showed the same behavior (Fig. 4f).

Principal component analysis (PCA)

For the biometric and nutritional parameters of the plant, the first two main components explained 94.2% of the total variance of the data, 79.8% of which were

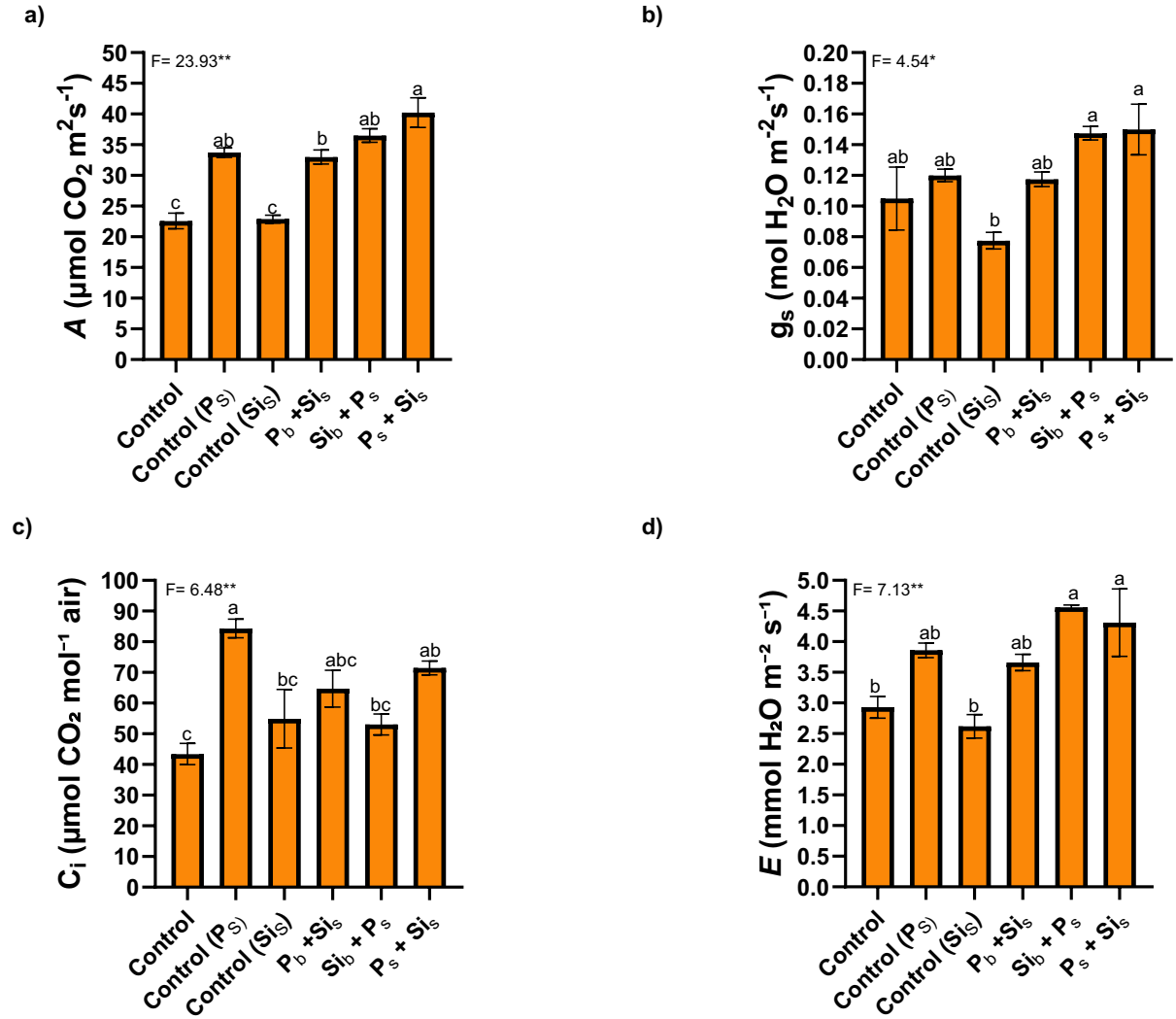


Fig. 3 Net photosynthetic rate (*A*) (**a**), stomatal conductance (g_s) (**b**), internal CO_2 concentration (C_i) (**c**), and transpiration rate (*E*) (**d**) of maize as a function of the applied treatments. Control: Without P and Si application. Control (P_S): 100 mg kg^{-1} of P applied at sowing; Control (Si_S): 480 mg kg^{-1} of Si applied at sowing; $P_b + Si_s$: 100 mg kg^{-1} of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s); $Si_b + P_s$: 480 mg kg^{-1} of Si added 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing; and $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si added together at sowing. Columns followed by the same letter do not differ from each other by the Tukey test at 5% significance. Error bars represent the standard error (n = 4). ** = Significant at 1%. * = Significant at 5%. NS = No significant

explained by PC1 (Fig. 5a). Consequently, PC2 maintained a lower variance (14.4%), which indicated a secondary axis of variation, associated with the concentration of Si in shoots. The Control treatment (Si_S) was grouped in the upper left quadrant, showing a positive association with Si concentration. On the other hand, the other treatments moved in the positive direction of PC1, with alignment of the collinear vectors (arrows) of dry mass, uptake of P and Si and height of the shoots (Fig. 5a).

The first two principal components (PC1 and PC2) explained 91.6% of the total variation in physiological parameters. A strong multivariate correlation was observed between these gas exchange variables. The $P_s + Si_s$ treatment presented a high score for these parameters. On the other hand, the Control treatment

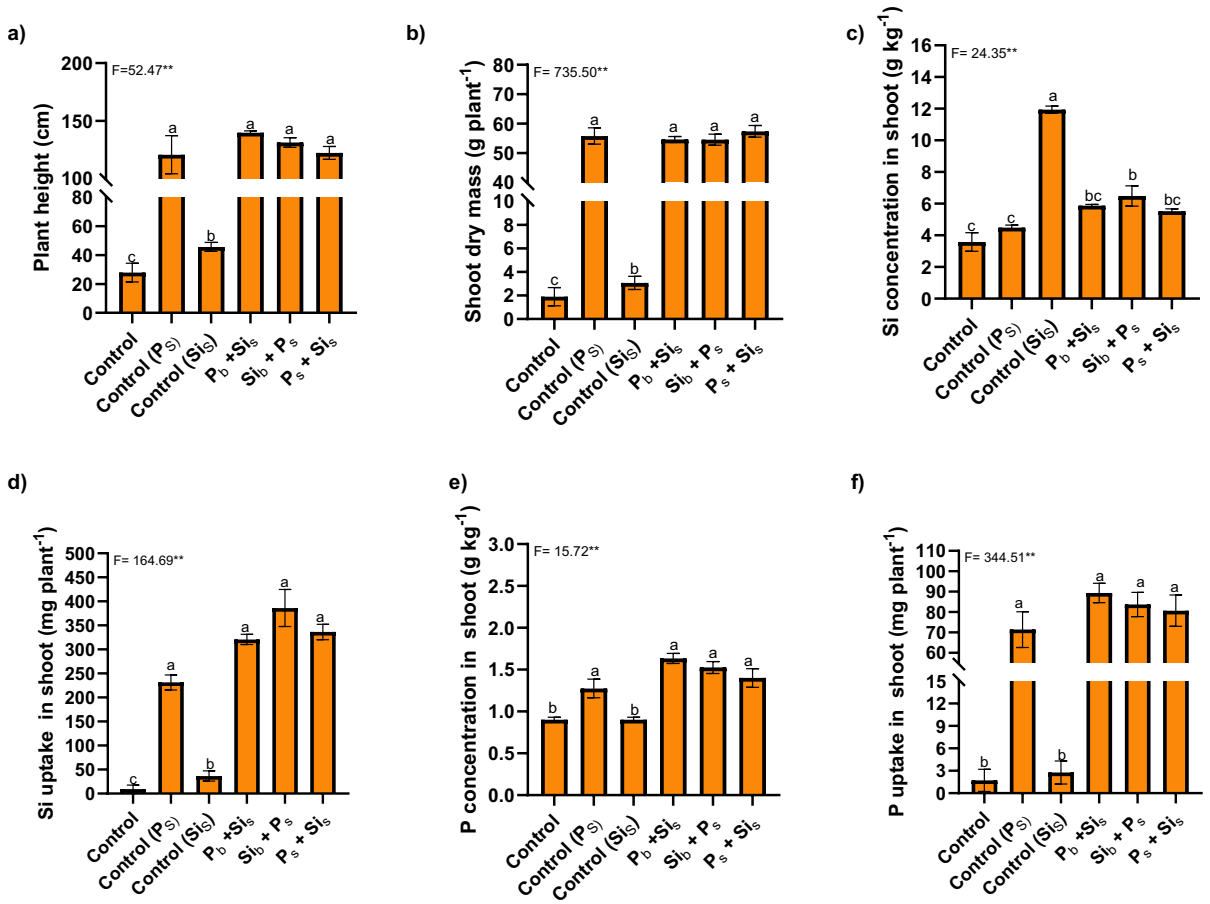


Fig. 4 Plant height (**a**), shoot dry mass (**b**), silicon concentration (**c**) and uptake in shoot (**d**), phosphorus concentration (**e**) and an uptake in shoot (**f**) of maize as a function of the applied treatments. Control: Without P and Si application. Control (P_s): 100 mg kg^{-1} of P applied at sowing; Control (Si_S): 480 mg kg^{-1} of Si applied at sowing; $P_b + Si_s$: 100 mg kg^{-1} of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s); $Si_b + P_s$: 480 mg kg^{-1} of Si added 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing; and $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si added together at sowing. Columns followed by the same letter do not differ from each other by the Tukey test at 5% significance. Error bars represent the standard error (n = 4). ** = Significant at 1%. * = Significant at 5%. NS = No significant

(Si_S) was positioned close to the vector of the internal concentration of CO_2 (C_i) (Fig. 5b).

The soil parameters showed greater data dispersion; The first two main components explained 68.6% of the data. PC1 separated the treatments mainly by the availability of P. Variables such as available P and Pi_{NaOH} had a greater influence of the treatments $P_b + Si_s$ and $P_s + Si_s$. The Control (Si_S) treatment stood out in PC2, strongly correlating with the available Si and Pi_{HCl}. On the other hand, the Control treatment was positioned on the opposite side of PC1, associated with Po_{NaOH} (Fig. 5c).

Discussion

The central hypothesis of this study was that silicon (Si) application prior to phosphate fertilization could increase phosphorus (P) availability in the soil and, consequently, in the plants. The results of this study demonstrated that Si can increase soil P availability (Fig. 1a), as reported in the literature (Schaller et al. 2022; Jiang et al. 2025; Cheraghi et al. 2025). However, no increase was observed in the concentration or uptake of P in the shoot of maize plants (Fig. 4ef). We also observed that the timing of application mainly

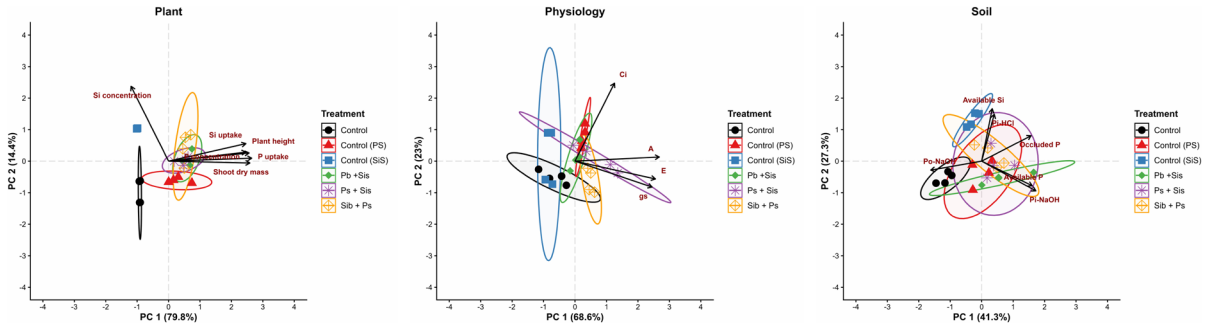


Fig. 5 Principal component analysis (PCA) biplots displaying the scores of the treatments and the loadings of the variables divided into three groups: (**a**) Plant parameters (plant height, shoot dry biomass, P and Si concentration and uptake); (**b**) Physiological parameters (A, g_s, C_i and E); and (**c**) Soil parameters (available P—M3, Pi_{NaOH}, Po_{NaOH}, Pi_{HCl}, occluded P, and available Si). The horizontal and vertical axes represent the first (PC1) and second (PC2) principal components, respectively, with their corresponding percentages of explained variance indicated in parentheses. The percentages of cumulative explained variance for the two first axes (PC1 and PC2) were 94.2%, 91.6% and 68.6% for panels (a) plant, (b) physiology and (c) soil, respectively. Vectors indicate the directional influence and loadings of the measured parameters. Circular and elliptical symbols represent individual scores, and the solid lines represent the 95% spatial confidence ellipses calculated around the treatment centroids. All datasets were standardized to unit variance prior to analysis (n = 4). Control (P_s): 100 mg kg^{-1} of P applied at sowing; Control (Si_S): 480 mg kg^{-1} of Si applied at sowing; $P_b + Si_s$: 100 mg kg^{-1} of P applied 30 days before sowing (P_b) and 480 mg kg^{-1} of Si at sowing (Si_s); $Si_b + P_s$: 480 mg kg^{-1} of Si added 30 days before sowing (Si_b) and 100 mg kg^{-1} of P at sowing; and $P_s + Si_s$: 100 mg kg^{-1} of P and 480 mg kg^{-1} of Si added together at sowing

influences the concentration of readily available P in the soil. The increase of 60.49% and 54.78% of available P for plants observed with the $Si_b + P_s$ treatment (Si applied 30 days before sowing and P applied at sowing) and $P_s + Si_s$ (P and Si applied at sowing) compared to the control with only P (Fig. 1a). This can also be observed in the increase of soil P saturation with the combined application of Si and P at sowing ($P_s + Si_s$) or with the application of Si before P ($Si_b + P_s$), demonstrating the potential of Si to reduce P sorption in tropical soils.

Some mechanisms reported in the literature may be involved in these findings, taking into account the conditions of the soil used in the study: The first is related to P-Si competition for the same adsorption sites (Carvalho et al. 2001; Sandim et al. 2014); it is reported that monosilicic acid competes for sorption sites with monodentate and bidentate ligands of the phosphate molecule (Schaller et al. 2019).

Although the binding energy of Fe and Al oxides for the monosilicic acid molecule is lower than that for phosphate (Parfitt 1979), it has been reported that monosilicic acid can compete with phosphate anions in clay minerals, and this mechanism depends on the concentrations of both compounds in the soil solution (Katz et al. 2021). It is known that pH influences Si dynamics in the soil (Dol Hamid et al. 2011; Meunier et al. 2018; Pallavi and Prakash 2019). The literature reports that Si adsorption is enhanced only under alkaline pH conditions, specifically between 9 and 10 (Haynes and Zhou 2020); thus, Si competition for P adsorption sites under acidic pH conditions is considered low. However, our P sorption saturation (%) data support that P desorption can occur even under acidic pH conditions, since in the study the pH variation among treatments was from 4.5 to 4.9 (Fig. S1) and an increase in the percentage of P saturation was noted in the $Si_b + P_s$ (Si applied 30 days before sowing and P applied at sowing) and $P_s + Si_s$ (P and Si applied at sowing) treatments (Fig. 2d). Corroborating these observations, Uhuegbue et al. (2026) verified that Si can interact with Fe oxides and increase P availability even under acidic conditions (pH 5.0). Those authors observed that Si competes for adsorption sites on goethite and hematite, consequently, reduces P adsorption. These mineral compounds are predominant in highly weathered soils, such as the one evaluated in this study, which supports our findings P sorption saturation (Fig. 2d).

In addition, the formation of Si-Al complexes may also have decreased the active sites for P adsorption; the formation of Al-Si complexes can occur under acidic pH conditions (Haynes 2014). This mechanism was also suggested by da Silva et al. (2026),

who studied the effect of increasing rates of P and Si under soil conditions similar to this one. In this study, the combination of these mechanisms may have prevented the transformation of P into less labile forms in the soil.

A study with soils developed from glacial deposits and with a sandy texture reported that the type of extractant influences the response to P availability in soils when Si is applied (Uhuegbue et al. 2024). In this study, both extractants showed responses regarding available soil P; however, the soil used in this experiment had a clayey texture and distinct chemical characteristics. Although the concentration of available soil P was higher when extracted by the resin method, the Mehlich-3 extractant showed the same behavior, and both were highly correlated with P uptake. The greater P extraction capacity by the resin is related to the mineralogy of the soil used in the experiment, which exhibits high concentrations of Fe and Al oxides (Table 1). Thus, a considerable fraction of P is associated with the surface of these compounds, where the ion-exchange resin acts similarly to plant roots, promoting the desorption of labile phosphate in equilibrium with the soil solution (Silva and Raij 1999). Conversely, Mehlich-3 extraction is sensitive to the P buffering characteristics of the soil, showing a reduction in its extraction capacity as soil buffering increases (Reis et al. 2020). Total P showed no difference among treatments (Fig. 2a), the literature reports that this can happen due to the high reserve of total P in the soil. Although a P rate of 100 mg kg^{-1} was supplied, this rate may not have been sufficient to alter the total P pool relative to what was already present in the soil (Olibone and Rosolem 2010).

The P fractionation demonstrated that although most of the P remained in the occluded fraction, the presence of Si improved P availability. The principal component analysis (PCA) demonstrates this behavior, especially in the treatments that received $Si_b + P_s$ and $P_s + Si_s$, which correlated with the labile P fractions (Fig. 5c). There was a trend toward an increase in the soil inorganic fraction (Pi_{NaOH}), demonstrating that during the experimental period, the influence of Si occurs in the more labile soil fractions, as observed by the labile P extracted by both extractants (Mehlich-3 and resin). The PCA demonstrated that plant-available P and the inorganic P bound to Fe and Al (Pi_{NaOH}) are associated with Si and P treatments ($P_b + Si_s$ and $P_s + Si_s$), while the organic P (Po_{NaOH}) was not associated with either individual or combined P and Si treatments. This behavior indicates that Si acts on the chemical equilibrium of P in the soil, favoring the permanence of P in more available forms in the soil. Furthermore, the absence of P application increases the organic forms of P in the soil, probably because there is lower microorganism activity in this environment; Si can increase the activity of microorganisms that decompose organic matter in the soil (Hömberg et al. 2021; Bezerra et al. 2025), however, this hypothesis should be further explored, since soil microorganism activity was not evaluated in this study. A correlation was also observed between available Si and calcium-bound P (Pi_{HCl}); the literature reports that Si can decrease the formation of P-Ca complexes through the stimulation of microorganism activity, which, consequently, can contribute to the exudation of organic acids (e.g., malate and succinate) that can solubilize these complexes (Jiang et al. 2025). In addition, Si promotes the formation of Si-Ca complexes, reduces Ca concentration in soil solution, and consequently increases P availability (Schaller et al. 2019).

Different from the effects observed in the soil, the combined application of Si and P, regardless of the application timing, did not increase the concentration and accumulation of P in the plant compared to the treatment that received only P. This may be related to the low P requirement of the maize hybrid used as the test plant, which requires a low amount of inputs for its production and is recommended for low-cost crops (link); additionally, the experiment was conducted over a 60-day period, and this timeframe may not have been sufficient to evaluate these variables, requiring additional studies with a maize hybrid more sensitive to P or with a lower P rate than the one used in this study. These findings indicate that although Si application alters available soil P, this response does not necessarily translate into increased plant P uptake under non-limiting P conditions or short-term crop cycles.

This behavior was also observed in the biometric parameters, but Si supplied alone contributed to greater dry mass production and plant height compared to the absolute control treatment; this effect has already been reported in the literature (Pavani et al. 2023; Jiang et al. 2025) and may be related to

the role of Si in improving plant development, such as increasing the root system and leaf area (Tripathi et al. 2021). Although the means test showed no significant effect on biometric parameters and P uptake as a function of the combined application of P and Si, the PCA clearly separated these parameters, grouping them with the $P_s + Si_s$, $Si_b + P_s$, and $P_b + Si_s$ treatments on the opposite side of the control. This clustering trend suggests a joint response of these variables to the combined application of Si and P, revealing effects that were not statistically significant in the individual means tests.

The increase in soil P availability improved the physiological parameters of maize; the $P_s + Si_s$ combination (P and Si at sowing) contributed to a higher photosynthetic rate and stomatal conductance. The single application of Si reduced stomatal conductance (g_s) without compromising photosynthesis compared to the absolute control treatment. The PCA also demonstrated that photosynthetic rate, stomatal conductance, and transpiration rate were influenced by the $P_s + Si_s$ treatment. However, biometric parameters such as height and dry mass proved to be dependent on P application, and there was no difference when Si was applied in combination with P, regardless of the timing of application. The role of P in photosynthetic parameters is reported in the literature and is related to increased energy transfer (ATP, ADP, and AMP), which plays an important role in carbon metabolism, directly influencing carbon assimilation and also sustaining the respiratory process of plants (Malhotra et al. 2018).

In addition to the effects of P nutrition, the higher stomatal conductance observed in plants that received $Si_s + P_s$ may be associated with Si mediated mitigation of Al toxicity. Silicon can interact with Al in the rhizosphere and root apoplast, promoting the formation of hydroxyaluminosilicate complexes and reducing aluminum phytotoxicity in plant roots. Consequently, this effect may improve root growth and function, potentially increasing plant water uptake and favoring stomatal opening (Deus et al. 2026; Hodson and Evan 2020; Kopittke et al. 2017). However, root growth and water use efficiency in maize plants were not evaluated in this study.

The improvement of plant photosynthetic processes mediated by Si is discussed in the literature (Debona et al. 2017; Rastogi et al. 2021); however, the processes involved are still not fully understood. In a review of the influence of Si on photosynthetic processes, it was shown that Si can improve photosynthetic processes through biochemical interactions, transcriptional, and metabolic reprogramming (see Mukarram et al. 2026); however, the physiological, biochemical, and molecular mechanisms underlying these responses were not investigated in the present study. Furthermore, although increases in photosynthetic rate and stomatal conductance were observed, the duration of the experiment did not allow assessment of whether these physiological responses would ultimately translate into greater grain yield in the maize genotype evaluated.

Conclusion

The results of this study demonstrated that Si application can be an alternative to increase P availability in tropical soils. The increase in soil P availability occurred with the application of Si before P or the joint application of P and Si. These findings were attributed to Si-P competition for the same adsorption sites or the formation of Si-Al complexes. Although this former mechanism is more intense in soils formed in temperate climates (slightly weathered), the P sorption saturation (%) data presented in this study indicates that this mechanism is also relevant in soils formed in tropical climates (highly weathered), which exhibit high concentrations of Fe and Al oxides.

The application of Si only or combined with P, regardless of the timing of P and Si application, did not increase P concentration and accumulation by plants, although available P increased in the soil. The application of Si in the absence of P contributed to better maize growth, but it was not superior to the application of P only. The supply of Si and P at sowing improved the photosynthetic parameters of maize plants.

Further studies evaluating lower soil P rates need to be conducted to verify the best management of Si application aiming to increase P availability. Furthermore, for future studies, it is recommended to use a maize genotype with higher P requirements.

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Authors' contributions JEP performed investigation, formal analysis, data curation, visualization, and wrote the original draft. APRS contributed to the conceptualization, methodology, formal analysis, visualization, data interpretation, drafting of the original manuscript, review and editing, supervision, and project administration. In addition, APRS led the restructuring of the manuscript, the development of the scientific discussion, and the critical revision and submission process. LJRS, ACFD, and LTB contributed to writing (review and editing). TSF performed physiological analyses. DMF contributed to conceptualization, writing (review and editing), supervision and project administration, resources, and funding acquisition.

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Data availability Are available.

Declarations

Ethics approval Not applicable.

Consent to participate All authors agreed with the content and all of them gave explicit consent to submit.

Consent for publication We have the consent of the authors for the publication.

Research involving human participants and/or animals Not applicable.

Informed consent Not applicable.

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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