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ORIGINAL PAPER

Foliar Spraying of Silicon Associated with Salicylic Acid Increases Silicon Absorption and Peanut Growth

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Abstract

Silicon (Si) combined with foliar spraying of salicylic acid (SA) can affect the absorption of this beneficial element. A study with Si non-accumulators plants (soybean and bean) observed that SA foliar spraying improved leaf absorption. However, this effect is unknown in peanut (*Arachis hypogaea*), a Si non-accumulator species. The aim of the present study was to assess the effect of applying Si to the leaves or roots, associated with foliar applications of SA, on Si absorption and dry weight production of peanut plants. An experiment was conducted with IAC OL4 peanut cultivars in pots filled with 6 L of sand. A randomized block design was used, in a 3 × 3 factorial scheme, as follows: Si application via leaves and roots in the form of monosilicic acid and the control (no Si) and three foliar applications of salicylic acid (0; 0.05; 0.15 mM), with five repetitions. The Si was supplied via nutrient solution (root) and leaves throughout the experiment, with three spraying treatments: at the end of the vegetative stage, onset of flowering and at the start of pod formation. The SA foliar sprayings were performed together with Si. Foliar silicon application was superior to its root counterpart at all SA concentrations. The greatest Si accumulation for root application was observed at a concentration of 0.05 mM of SA. Shoot dry weight and root dry weight production increased with Si. SA application, at a concentration of 0.05 mM, especially when associated with foliar Si, favored Si absorption and dry weight production in peanut plants. Foliar spraying of Si with the addition of salicylic acid is a new strategy for silicon supplementation in Si non-accumulators.

Keywords *Arachis hypogaea*; beneficial element · Plant hormone · Leaf silicon application · Plant nutrition

1 Introduction

Silicon (Si) is considered beneficial to plants, mainly to accumulator plants, since it provides greater resistance to biotic and abiotic stress, enabling better performance in adverse field conditions [1]. However, Si absorption varies among plant species and occurs via leaves and roots in the form of monosilicic acid, mediated by specific carriers exhibiting high xylemic and low phloemic mobility [2] with legumes considered Si non-accumulators [3]. These plants exhibit restricted root absorption of the element [4], given the lack of specific Si transporters in the roots [5].

In legume plants, such as peanut (*Arachis hypogaea*), classified as Si non-accumulators [5], the absorption process occurs predominantly by passive diffusion, given the low effectiveness of transporters such as LSi1 (root surface) and LSi2 (from the root to the xylem) in the root cells [6–8]. In addition, although Si absorption may occur, the Si absorbed by non-accumulating plants, such as peanut, tends to accumulate in the roots [9]. Despite the low Si absorption by legumes, supplying this element was beneficial to peanut plants, since reports have found that its application in a nutrient solution relieves stress such as Cd [10] and Al [11, 12] toxicity. The authors reported the benefits of Si by decreasing Al absorption and reducing oxidative stress and lipid peroxidation in the peanut under Al and Cd toxicity.

One strategy to increase Si content in shoots and overcome low root absorption would be to supply it through the

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leaves, in soluble sources of Si, which can favor its accumulation in leaf tissue. Although foliar application of Si is not a common practice in peanut farming, only one investigation reported positive results in peanut plant production [13]. Studies on Si foliar spraying in non-accumulator plants are incipient [14], especially those with innovative sources such as monosilicic acid, which is already in the form that the plant absorbs (H_4SiO_4) [15]. In solution, however, Si may polymerize, depending primarily on its concentration and pH value [16], possibly compromising its absorption. A stabilizer such as salicylic acid, which reduces the pH of the spray solution, can be used to inhibit Si polymerization and indirectly favors its absorption, since with decreasing pH, monosilicic acid, a form of Si absorbed by plants [17], has greater stability [18]; however, this has yet to be confirmed.

Additionally, foliar spraying of salicylic acid (SA) has a bioregulatory effect on plant growth, thereby benefitting leaf biomass production and photosynthetic activity [19] and increasing tolerance to biotic and abiotic stress [20]. However, applying high concentrations of SA may provoke phytotoxicity and reduce yields [14, 21, 22].

A study that assessed Si (3.6 g L^{-1}) and SA foliar application (210 mg L^{-1} or 1.5 mM) in Si non-accumulators (soybean and bean) observed that SA foliar spraying improved leaf absorption [14]. The authors attributed this fact to the isolated effect of the factors (Si and SA), since SA would have increased CO_2 uptake and stomatal opening, thereby raising Si absorption. However, in rice, a Si accumulator plant, no foliar spraying effect on Si absorption was observed when combining Si and SA [23]. Since these results are confined to two crops, information is needed on other species in order to determine whether the benefit of SA foliar spraying on Si absorption depends or not on the application method (via roots or leaves).

Although there is an indication of the interaction benefits of Si and SA, it was not known whether these would be more evident in root or leaf nutrition for Si non-accumulating plants, such as peanut. The combination of Si and SA may contribute to optimizing silicon supplementation in non-accumulator plants, thereby raising the possibility of a response and crop sustainability. In this respect, it is important to test the hypotheses: a) foliar-applied Si may be better than its root-applied counterpart in terms of increasing absorption in peanut plants and; b) SA foliar spraying at a particular concentration may raise Si absorption, depending on the application method, and favor peanut plant growth.

As such, the aim of the present study was to assess the effect of Si foliar and root application, associated with SA foliar applications, on Si absorption and dry weight production in peanut plants.

2 Material and Methods

2.1 Experimental Conditions

The experiment was conducted with peanut plants (IAC OL4 cultivar), using a soilless growing medium in a greenhouse between August and December 2016. During this experimental period, average relative humidity, and maximum and minimum temperature were measured (Fig. 1).

There was a significant variation in average relative humidity (74 ± 6.5%), as well as minimum (17.8 ± 3.5 °C) and maximum temperature (45.7 ± 7.3 °C). The plants were submitted to temperatures higher than the range considered optimal for peanut growth, which is between 22 and 30 °C [24]. At the time of foliar application, average relative humidity was above 60%.

The average length of the day in the greenhouse during the experiment was 7.7 ± 0.6 h.

Peanut seeds were planted directly in the pots, at a depth of 5 cm, without the need to disinfect them.

2.2 Experimental Design

A randomized block design was used, in a 3 × 3 factorial scheme, consisting of Si application via roots, leaves and a control, and three foliar salicylic acid concentrations (0; 0.05; 0.15 mM), with five repetitions. The experimental unit consisted of a polypropine pot (upper diameter: 16 cm; lower diameter: 11 cm; height: 33 cm) filled with 6 L of sand, previously washed with water, 1% HCl solution and deionized water, containing two plants per pot.

2.3 Silicon and Salicylic Acid Application

Root Si was applied with monosilicic acid, stabilized with polyethylene glycol 400 (14.04 g L^{-1} of Si and pH 1.4) throughout the experimental period, and added to the nutrient solution at a concentration of 2 mM of Si. Polyethylene glycol 400, a low molecular weight polyethylene glycol with hydrophilic characteristics, is highly soluble in water and exhibits a stabilizing function [25]. The nutrient solution was applied immediately after the addition of Si, and pH was adjusted with NaOH (1 M) to between 5.5 and 6.5.

The same source was used at a concentration of 35.7 mM of Si and pH was adjusted to between 6.5 and 7.0, which may favor chemical compatibility if mixed with fertilizers, to leaf application of Si. The silicon spray solution was applied immediately after its preparation, using a handheld sprayer for total coverage of plant shoots, and the pot surface covered with cotton fabric.

The literature reports that the 2 mM treatment is often used in the nutrient solution to provide Si via the root [26]. For the other treatments, a laboratory test was carried out using a combination of different solutions, with increasing

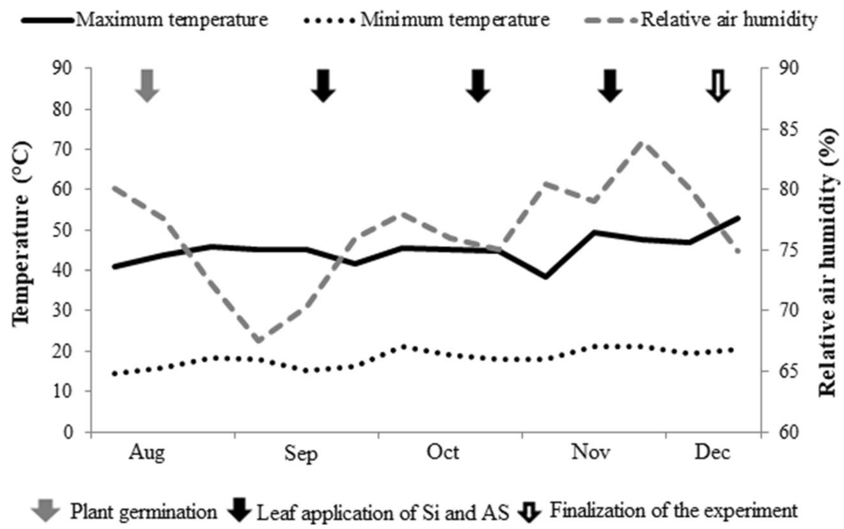

Fig. 1 Minimum and maximum temperature and relative humidity during the trial period

concentrations of Si and SA and estimated the polymerization of the solution. The combination of 35.7 mM Si and 0.15 mM SA guaranteed the highest concentrations of these elements in the solution without the occurrence of polymerization. From this information, we added a treatment with a lower SA concentration (0.05 mM SA) to determine if this concentration could be decreased without causing damage to the variables analyzed. This laboratory test was needed given the lack of information in the literature.

A solution with SA was prepared for foliar spraying at the concentrations of each treatment. The pH was raised to 11 with the addition of NaOH (1 M) in order to increase solubility. The SA solution was added to the silicon spray solution for the foliar treatment with Si + SA. In all the treatments, the pH of the solution with SA was adjusted to between 6.5 and 7.0 with the use of HCl (1 M).

Foliar applications occurred in three stages: at the end of the vegetative stage (V), onset of flowering (F) and the start of pod formation (PF). The volume of the solution applied varied according to plant size, namely 4.8; 9.6 and 9.6 mL of the solution with Si for the first, second and third spraying, respectively. Temperature (°C) and relative humidity (%) were measured during the leaf sprayings, obtaining the following values: 20.1 °C and 65%; 22.7 °C and 68%; and 21.1 °C and 81%, respectively, considered adequate for leaf spraying.

The plants were irrigated with deionized water for seven days after planting (DAP). Next, the nutrient solution [27] was applied, with changes in the iron source from Fe-EDTA to Fe-EDDHMA, at 10% ionic strength, increasing to 25% for 7 days, and later to 50% until the end of the experiment. The nutrient solution was applied to maintain 70% water retention in the substrate, with pH adjusted to between 5.5 and 6.5, using an HCl (1 mol L^{-1}) or NaOH solution (1 mol L^{-1}). A weekly 500 mL application of deionized water was made to each pot in order to drain the substrate and avoid salinization and after 2 h the nutrient solution was once again supplied.

2.4 Silicon Accumulation and Root and Shoot Dry Mass Production

At the end of the growing cycle (130 DAP) the plants were collected and separated into a root system and shoots. For the root Si treatment, Si accumulation was measured in the upper, middle and lower third of the leaves and stem.

The plant material was washed with deionized water, detergent solution (0.1%), HCl solution (0.1%) and deionized water, packed in paper bags and dried in a forced air oven at 65 °C ± 5 until dry weight stabilized, then weighed to determine the dry weight of different plant parts.

Next, the samples were ground in a Wiley mill and then Si content was analyzed based on alkaline digestion with H_2O_2 and NaOH, followed by colorimetric reading in a spectrophotometer, in line with the methodology described by Korndörfer, Pereira and Nola (2004). Silicon content and dry weight production were used to calculate Si in the different plant parts.

The peanut plant shoots were stratified into upper, middle and lower third in order to assess accumulation in different plant parts resulting from the root Si treatment.

2.5 Statistical Analyses

The data were submitted to bidirectional analysis of variance (ANOVA) after determining homogeneity of variances. The Shapiro-Wilks W test was used to test data normality. The data were then submitted to analysis of variance and when the F-test was significant, the measures were compared using Tukey's test at 5% probability, applying Sisvar® software [28].

3 Results

Foliar silicon application was superior to its root counterpart at all SA concentrations (Fig. 2). However, even with limited

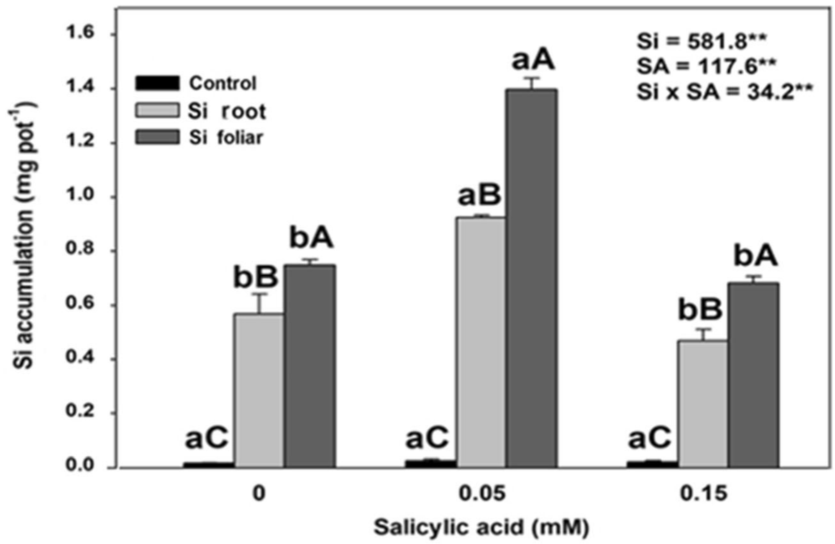

Fig. 2 Silicon accumulation in peanut plant shoots as a function of salicylic acid (SA) concentration and silicon (Si) application modes. ** significant by test Fat 1% of probability. Different lowercase and uppercase letters show differences between SA concentration and between Si application modes, respectively, by Tukey test at 5% of probability

root absorption, Si root application enabled greater accumulation of the element in peanut plants, when compared to the control treatment. Applying 0.05 mM of SA raised Si absorption, regardless of application method, while 0.15 mM of SA caused a reduction in Si accumulation, not differing from the treatment without SA, irrespective of application mode (Fig. 2).

The greatest Si accumulation for root application was observed at a concentration of 0.05 mM of SA, followed by 0 and 0.15 mM (Fig. 3a). Despite the difference in SA concentrations, the distribution pattern of Si in the plant was similar. Most of the Si (around 60%) accumulated in the middle and upper third of the shoots (Fig. 3b). At the highest SA concentration (0.15 mM), Si accumulation in the roots declined in relation to plants without SA application (Fig. 3b).

Shoot dry weight (SDW) (Fig. 4a) and root dry weight (RDW) (Fig. 4b) production increased with Si, irrespective of the SA concentration applied, except at 0.15 mM. SDW rose with both Si foliar and root applications, in the absence of SA and at a concentration of 0.05 mM. SDW was higher in plants that received 0.05 mM of SA, compared to the other treatments. Applying 0.05 mM of SA increased the SDW of plants that received Si, independent of application mode, but the highest concentration (0.15 mM) decreased SDW production, compared to the absence of SA and a concentration of 0.05 mM (Fig. 4a).

RDW was higher with root Si application, compared to the treatment with no Si, at concentrations of 0.05 and 0.15 mM of SA. Applying SA at 0.05 mM increased the RDW of plants that received Si via roots or leaves, compared to controls.

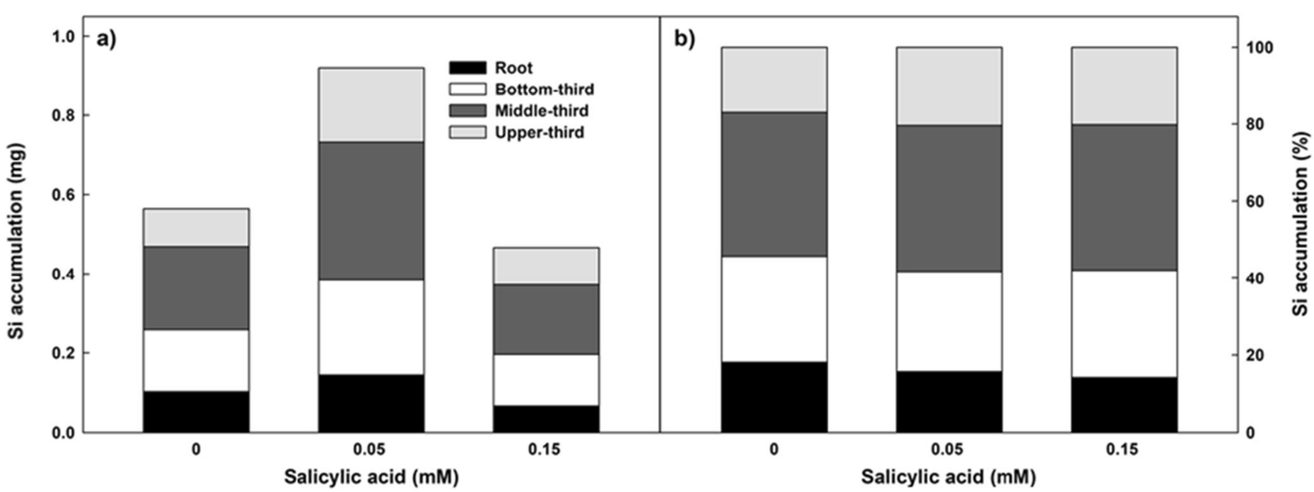

Fig. 3 Silicon accumulation in root and shoots (lower, middle and upper third) in g per plant (**a**) and % (**b**) of peanut plants as a function of salicylic acid (SA) concentration with Si supply by root

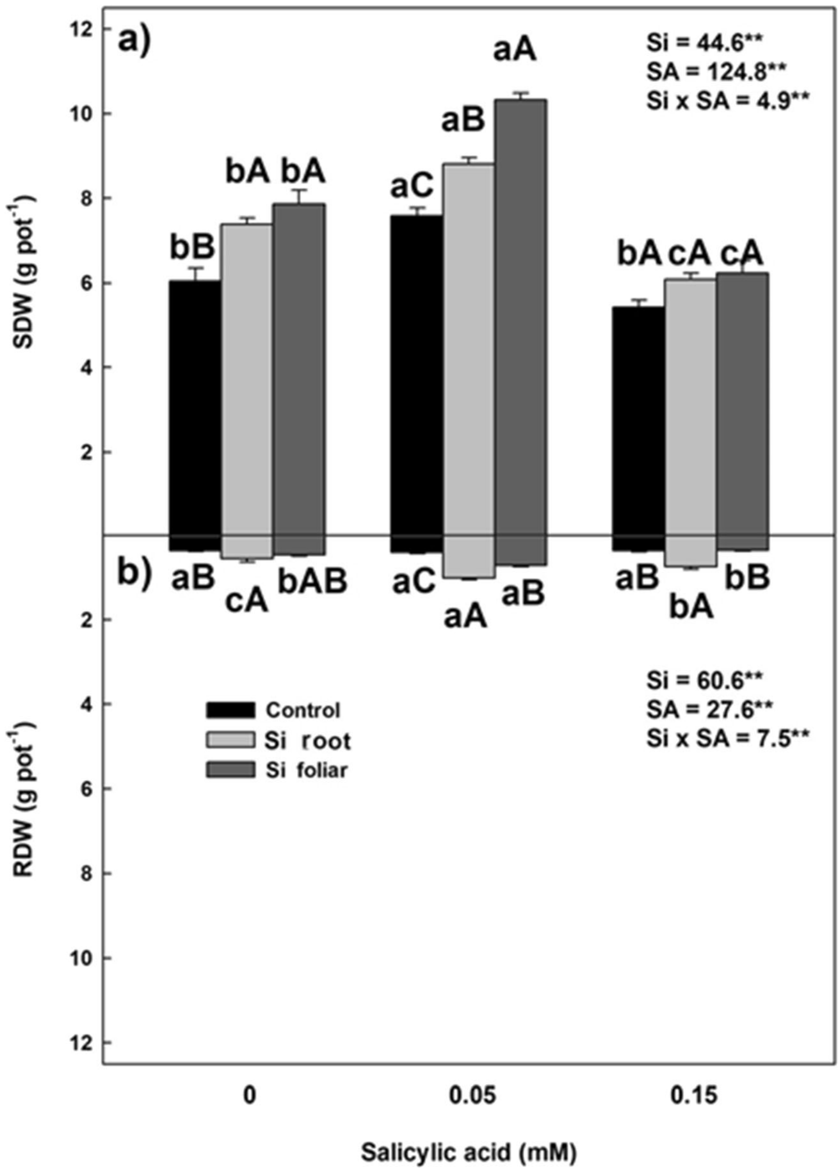

Fig. 4 **a** Shoot dry weight (SDW) and **b** root dry weight (RDW) of peanut plants as a function of salicylic acid (SA) concentration and silicon (Si) application modes. ** significant by test Fat 1% of probability. Different lowercase and uppercase letters show differences between SA concentration and between Si application modes, respectively, by Tukey test at 5% of probability

However, applying SA in the treatment without Si did not influence RDW (Fig. 4b).

4 Discussion

Si absorption occurs by passive diffusion and with the participation of transporters located in the exoderm and endotherm of roots [6, 29]. In peanut plants, classified as Si non-accumulators [5], the increase in Si accumulation in the root treatment (Fig. 2) indicates restricted Si absorption by this legume. As observed in tomato plants [29], the absorption process may have occurred in peanut plants predominantly by passive diffusion, given the low effectiveness of transporters such as Lsi1 (root surface) and Lsi2 (from the root to the xylem) in the root cells [6–8].

The absorbed Si is transported to the shoot and deposited as hydrated amorphous silica, initially in the youngest and later the oldest tissues [30, 31]. Silica accumulation is greater in the shoot than in the roots, and accumulates faster in the oldest than youngest leaves [32, 33], a finding also observed in peanut plants (Fig. 3). This greater Si accumulation in the oldest and intermediate leaves indicates low phloem mobility of the element in the plant, as widely reported in a number of species [34]. However, the larger amount of Si in the shoot compared to the roots indicates that the xylem transport of Si in peanut plants occurs from the roots to the leaves, which is specific to this species, since found that legumes generally accumulate more Si in the roots [5].

The source of Si used as a monomere was efficient in increasing the accumulation of the element in the plant, mainly in foliar application associated with salicylic acid (0.05 mM) (Fig. 2). A similar result occurred with this source using foliar spraying, but without adding SA, as reported in soybean, bean and peanut [13] and cotton [35]. Thus, Si in acid form and associated with SA may have decreased the polymerization reactions of Si, favoring its absorption and suggesting that the combination of these elements is a viable strategy for supplying Si to crops with limited root absorption.

Foliar Si application resulted in higher SDW when compared to root application. This is because leaf spraying was more efficient in raising Si accumulation in the shoot due to restricted absorption by the roots, since the peanut plant is a Si non-accumulator [5]. The beneficial effect of Si foliar spraying (0.02 g L^{-1}) in the form of stabilized silicic acid has also been reported by other authors for bean and peanut [13].

The most noteworthy result was that SA foliar spraying at a concentration of 0.05 mM associated with Si application via roots or leaves, increased Si accumulation (Fig. 2), and SDW (Fig. 4a) in peanut plants. Thus, the present study confirms the hypothesis that foliar sprayed SA improves Si absorption, thereby benefiting peanut plant growth. A similar effect was observed in bean plants [14] and cotton [36].

However, in the present study, the highest SA concentration (0.15 mM) compromised plant growth in relation to the treatment without the hormone. This antagonistic effect of SA was also observed in tomato [37] and bean [14] plants at the most widely used concentration (1.5 mM of SA). The plant response to this hormone depends on the time of application, form of usage and environmental conditions [38]. It is important to underscore that Si application can also mitigated the antagonistic effect of SA at the highest concentration (0.15 mmol L^{-1}), favoring dry weight production, especially in plants that received Si via the roots (Fig. 4).

In conclusion, applying SA at a concentration of 0.05 mM, especially when associated with foliar Si, favors Si absorption and dry weight production in peanut plants. Foliar Si spraying with the addition of salicylic acid is a new strategy for silicon supplementation in Si non-accumulator plants.

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