Growth and nutrient uptake of coffee seedlings cultivated in nutrient solution with and without silicon addition

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ABSTRACT

In recent years, the application of silicon (Si) in crops, including coffee, has become a common practice. The objective of this study was to assess the silicon uptake by coffee seedlings and its effects on plant growth, water and macro and micronutrient uptake. The research was conducted using nutrient solution in a greenhouse at the Departamento de Fitotecnia da Universidade Federal de Viçosa, in a completely randomized design with two treatments (with and without silicon) and three replications. Each plot consisted of three plants grown in a 800 mL vessel containing the treatment solutions. At every three days, water consumption, the concentration of OH^- and the depletion of Si and K were assessed in the nutrient solutions. After 33 days, the plants were assessed with regard to their fresh and dry weight of leaves, roots and stem, shoot height and total length of the plant (shoot and root). Number of leaves and internodes, and the content and accumulation of silicon, macro, and micronutrients were also determined. The consumption of water, the amount of potassium uptake and, biomass accumulation were greater in plants grown in solution without silicon addition. However, the concentration of OH^- in the solution and the amount of silicon uptake were greater in plants grown in solution with added silicon. Silicon accumulation was greater in leaves than in stem and roots. Silicon decreased coffee plant accumulation of phosphorus, potassium, calcium, zinc, copper and iron.

Key words: *Coffea arabica* L., mineral nutrition, nutrient uptake, biomass.

RESUMO

Crescimento e absorção de nutrientes pelo cafeeiro cultivado em solução nutritiva com e sem adição de silício

A adubação silicatada do cafeeiro promove alteração da nutrição da planta e de seu crescimento. Assim, a determinação da absorção de silício e sua influência na absorção de macro e micronutrientes pelas plantas são essenciais para avaliar as implicações deste elemento na fisiologia vegetal, bem como no manejo adequado da cultura. O objetivo deste trabalho foi avaliar a absorção de silício por plantas de café e seu efeito no crescimento e na absorção de outros nutrientes. A pesquisa foi conduzida em casa de vegetação do Departamento de Fitotecnia da Universidade Federal de Viçosa, em Viçosa, Minas Gerais, Brasil. O delineamento utilizado foi o inteiramente casualizado, com dois tratamentos (com e sem adição de silício) e três repetições, cada uma delas composta por três plantas. Foram retiradas alíquotas, a cada três dias, das soluções nutritivas e avaliadas as quantidades de silício e potássio absorvidas, bem como o consumo de água por plantas de café, além da concentração de OH^- na solução nutritiva. Ao final de 33 dias, as plantas foram avaliadas quanto à massa de matéria fresca e seca de folhas, raízes e caule; altura da parte aérea e comprimento

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total da planta (parte aérea e raiz); e número de folhas e entrenós, sendo determinados os teores e acúmulo de silício e nutrientes. O consumo de água, a quantidade absorvida de potássio e acúmulo de biomassa foram maiores nas plantas em solução sem adição de silício, enquanto a concentração de OH^- na solução e a quantidade absorvida de silício foram superiores nas plantas em solução com adição de silício. O acúmulo de silício foi maior nas folhas do que no caule e raízes. O silício diminuiu o acúmulo de fósforo, potássio, cálcio, zinco, cobre e ferro em mudas de cafeeiro.

Palavras-chave: *Coffea arabica* L., nutrição mineral, acúmulo de nutrientes, biomassa.

INTRODUCTION

Si is not considered essential to plant growth, but it has provided benefits for several species (Ma, 2004). This element is absorbed by the plant in the form of monosilicic acid (H_4SiO_4) along with water (mass flow) and accumulates mainly in the maximum perspiration areas as polymerized silicic acid. It promotes the effective control of plant diseases (Amaral *et al*., 2008; Guével *et al*., 2007; Pozza *et al*., 2009) and has been associated with reduced effects of harmful chemical and physical agents (Zhu *et al*., 2004, Ma & Yamaji, 2006). The benefits of Si can be observed in the growth and production of many grasses such as rice, oats and maize (Wang *et al*., 2004, Hossain *et al*., 2007; Zanão Júnior *et al*., 2009) and in some species that are not grass, such as tomatoes and lettuce (Lana *et al*. 2003; Resende *et al*., 2005).

The mechanisms usually considered to explain the beneficial effects of Si are related to indirect actions caused by the deposition of Si in the leaves, resulting in greater tissue rigidity. The leaves become more erect, favoring the incidence of light, greater CO_2 uptake and decreased excessive perspiration, allowing increased photosynthetic rate (Hattori *et al*., 2005; Ma & Yamaji, 2006). Other indirect effects of Si in the plant include: reduced toxic accumulation of iron and manganese and other heavy metals, like aluminum, and increased phosphorus uptake (Zhu *et al*., 2004).

In wheat and maize, Si promoted increased plant resistance to aluminum toxicity by the formation of aluminum silicate and aluminum silicate hydroxide caused by the release of organic acids in root apex (Kidd *et al*., 2001). In leaves, Si can increase the contents of hemicellulose and lignin, increasing the stiffness of the cells, as Hossain *et al*., (2007) have observed in oats. Pozza *et al*. (2004) have reported changes in coffee plant nutrition caused by silicon fertilization, increased enzyme activity, such as peroxidase and polyphenoloxidase and the presence of phytoalexin, which according to the authors, suggest the hypothesis that silicon is associated with plant defense reaction.

The different effects of Si may be associated with the ability of some plants to accumulate Si in their tissues. Plants can be divided into groups in relation to their silicon concentration. The groups include: accumulators, which contain 10% to 15% silicon oxide, intermediates, with 1% to 5% silicon oxide content, and non-accumulators (<0.5% silicon oxide), with most of the dicotyledons, such as legume species and many tree species (Takahashi *et al*., 1990). According to Pozza *et al*. (2004), new theories on disease resistance encouragement have led some researchers to study Si in non-accumulator species, such as the dicotyledons.

In rice, the presence of Si in its nutrient solution has altered phosphorus, iron, manganese, boron and calcium uptake (Silva & Bohnen, 2001). However, also for rice, Silva & Bohnen (2003) have found that plants exposed to different levels of Si and Ca are not affected, as far as nutrient uptake is concerned. Responses in nutrient uptake changes for plants grown with Si have also been observed for dicotyledons such as moringa (*Moringa oleifera* Lam.; Miranda *et al*., 2002) and potato (Pulz *et al*., 2008). Despite the acknowledged importance of the effects of Si on nutrient uptake, no alterations on coffee plants have been found yet.

Determining Si uptake and its influence on coffee plant absorption of macro and micronutrients is essential for the approval of management practices that include the use of Si in crop fertilization. Thus, the objective of this study was to assess the silicon uptake by coffee seedlings and its effects on plant growth, water and macro and micronutrient uptake.

MATERIALS AND METHODS

The research was conducted using nutrient solution in a greenhouse at the Departmento de Fitotecnia da Universidade Federal de Viçosa, using *Coffea arabica* L. seedlings, of the Catuaí Amarelo variety (yellow cherry).

The experimental design was completely randomized, with two treatments (concentrations of Si in the nutrient solution: 0 and 2 mmol L^{-1}) and three replications, with three plants per pot.

Newly germinated seedlings were transplanted into 20 L plastic containers, containing the nutrient solution proposed by Hoagland & Arnon (1950), with half of the original ionic strength, and kept under continuous aeration for 60 days.

After this period, the seedlings were transferred to polyethylene pots containing 800 mL nutrient solution previously evaluated for coffee, arranged in three plants per pot. The treatments applied consisted of complete nutrient solution with and without Si addition.

The nutrient solution included the following macronutrients and micronutrients: 3.01 mmol L^{-1} of N; 0.5 mmol L^{-1} of P; 1.61 mmol L^{-1} of K; 2.25 mmol L^{-1} of Ca; 0.935 mmol L^{-1} of Mg; 1.75 mmol L^{-1} of S; 45.0 μmol L^{-1} of Fe; 0.15 μmol L^{-1} of Cu; 0.65 μmol L^{-1} of Zn; 23.0 μmol L^{-1} of B; 6.3 μmol L^{-1} of Mn and 0.5 μmol L^{-1} of Mo.

In the nutrient solution containing Si, this element was supplied to the concentration of 2 mmol L^{-1}, with a product called Sili-K®, which has 12.2% of SiO_2 in its composition.

The nutrient solutions were continuously aerated and renewed at every nine days. The pH was adjusted every three days for the value of 5.5 ± 0.2, using HCl 0.1 mol L^{-1} or NaOH 0.1 mol L^{-1} solutions.

In order to verify Si uptake of coffee seedlings, at every three days, after completing the volume of the pots with water and correcting the pH, a 5 mL aliquot was taken from the nutrient solution of each pot, and then the Si concentration of the sample was determined. Si concentration was determined using the molybdenum blue colorimetric method at 660 nm (Korndörfer *et al*., 2004 with modifications), and the concentrations of Si in the samples were estimated based on the calibration curve prepared from standard solutions of Si. To confirm coffee plant nutrient uptake, potassium was used as an indicator, and its concentration was determined in samples collected every three days, using a flame photometer.

To determine plant water consumption, the experimental units were weighed every three days, and the water consumed was restored up to the initial weight of each experimental unit. Data for water loss by evaporation was obtained by loss of water in pots that had no plants. Such loss was taken into account in the calculation of water consumption in each experimental unit.

The concentration of OH^- in the nutrient solutions with and without Si was determined indirectly by pH measurement, using the potentiometric method. Thus, from the pH values obtained, pOH values for solutions were found, and OH^- concentrations were then determined.

At 33 days of cultivation, the plants were harvested and oven dried at a 60° C until they reached a constant weight to determine the dry matter. Plants were assessed with regard to their fresh and dry weight (stem, root, and leaf), shoot height and total length of the plant (shoot and root) in centimeters. Number of leaves and internodes, and the uptake of Si, content and accumulation of silicon, macro, and micronutrients in leaves, stem and roots were also determined. Si contents were determined by atomic absorption spectrophotometry, according to the procedure described by Korndörfer *et al*. (2004). N, P, K, Ca, Mg, Zn, Cu, Fe and Mn contents in the plants of each treatment were determined according to the method described in EMBRAPA (1997).

Data were submitted to analysis of variance, and means were compared by F test at 5% probability. Regression equations for quantitative factors were estimated with the aid of the computer software SAEG 9.0 (Euclydes, 2007).

RESULTS AND DISCUSSION

Both the solution with Si and without Si addition had this element present in their composition (Table 1). Coffee seedlings absorbed more Si when it was added to the solution. According to Hattori *et al*. (2005), although Si is an abundant element in nature, its availability to plants in soil solution is usually low, thus its uptake is reduced, especially for dicotyledons. However, Mitani & Ma (2005) have found increased absorption of Si in tomato plants subjected to greater concentrations of this element, which in this study was also confirmed for coffee.

Plants grown in solution without Si had greater uptake of K (Table 1). Such difference may be related to plant perspiration rate, since, in treatment without Si, plants had greater water uptake and that the uptake of K follows the perspiration flow. According to Ma & Yamaji (2006), Si is associated with several indirect effects, including the reduction of transpiration, which may explain the greater consumption of water of plants that did not receive Si.

OH^- concentration in the solutions was greater where Si was added (Table 1). The difference in concentration of OH^- is a function of the differential rate of cation and

Table 1. Total water consumption, total amount of Si and K absorbed by coffee plants cultivated in a nutrient solution with and without Si addition, and median concentration of OH^- in solution

Variables	With Si	Without Si	Difference
Water consumption (mL)	148.900	236.700	87.800*
Absorption of Si (mg)	0.072	0.007	0.065*
Absorption of K (mg)	10.404	12.937	2.533*
Concentration of OH^{-**}(mg)	0.094	0.055	0.039*

* Significant to 5% by the F test.

** Samples taken every each three days

anion absorption, since the extrusion or intrusion of H^+ is related to the balance of positive and negative charges of the ions absorbed. In general, there was a greater nutrient uptake by plants grown without Si, except for the Mn accumulated by the leaves, and especially by the stem (Table 2).

The Si content was significantly higher in leaves and roots of plants grown in solution in which it was added Si and accumulation of Si was significantly higher only in the leaves (Table 2) of the plants grown in this solution. According to Oliveira & Castro (2002) and Lana *et al*. (2003), the accumulation of Si is higher in regions where water is lost through perspiration, i.e. the leaf epidermis near the guard cells of stomata. Similar results to those found for coffee in this work were found by Luz *et al*. (2006) for lettuce. The authors, however, found no significant effect on the content of Si in the roots.

Coffee plants were efficient in absorbing Si provided and move it from roots to shoots at the end of 33 days (initial period of growth), a fact also observed in the early

Table 2. Content and accumulation of Si, macro and micronutrients in leaves, stems and roots of coffee plants grown in nutrient solution with and without Si addition, over 33 days

Nutrients	Plant parts	Content			Accumulation		
		Treatment			Treatment		
		With Si	Without Si	Difference	With Si	Without Si	Difference
		g kg^{-1}			mg plant^{-1}		
Si	Leaves	5.00	1.83	3.17*	7.17	3.22	3.95*
	Stem	1.00	1.40	0.40^{ns}	0.34	0.61	0.27^{ns}
	Roots	6.17	2.13	4.04*	2.58	1.16	1.42^{ns}
N	Leaves	31.07	28.53	2.54^{ns}	44.58	49.82	5.24^{ns}
	Stem	16.11	18.41	2.30^{ns}	5.54	8.04	2.50^{ns}
	Roots	22.55	22.09	0.46^{ns}	9.57	12.73	3.16^{ns}
P	Leaves	1.69	1.99	0.30^{ns}	2.42	3.47	1.05*
	Stem	1.62	1.96	0.34^{ns}	0.56	0.88	0.32*
	Roots	2.91	5.80	2.89^{ns}	1.27	3.37	2.10^{ns}
K	Leaves	25.81	26.21	0.40^{ns}	37.11	45.79	8.68^{ns}
	Stem	25.14	25.94	0.80^{ns}	8.71	11.62	2.91*
	Roots	34.75	33.95	0.80^{ns}	14.62	19.39	4.77*
Ca	Leaves	13.16	11.73	1.43^{ns}	18.70	20.56	1.86^{ns}
	Stem	4.99	4.90	0.09^{ns}	1.73	2.19	0.46*
	Roots	6.56	10.79	4.23^{ns}	2.84	6.27	3.43^{ns}
Mg	Leaves	3.28	3.43	0.15^{ns}	4.70	6.02	1.32^{ns}
	Stem	2.48	2.69	0.21^{ns}	0.86	1.22	0.36^{ns}
	Roots	6.39	6.37	0.02^{ns}	2.72	3.68	0.96^{ns}
S	Leaves	1.60	1.59	0.01^{ns}	2.30	2.78	0.48^{ns}
	Stem	1.44	1.70	0.26^{ns}	0.50	0.76	0.26^{ns}
	Roots	6.09	5.04	1.05^{ns}	2.52	2.88	0.36^{ns}
		mg kg^{-1}			mg plant^{-1}		
Zn	Leaves	11.624	11.523	0.101^{ns}	0.017	0.020	0.003^{ns}
	Stem	15.736	16.159	0.423^{ns}	0.005	0.007	0.002^{ns}
	Roots	22.470	32.961	10.491*	0.010	0.019	0.009*
Cu	Leaves	2.919	12.220	9.301*	0.004	0.022	0.018*
	Stem	1.765	4.684	2.919^{ns}	0.001	0.002	0.001^{ns}
	Roots	8.826	8.418	0.408^{ns}	0.004	0.005	0.001^{ns}
Mn	Leaves	135.629	68.565	67.064*	0.192	0.120	0.072^{ns}
	Stem	72.494	35.320	37.174*	0.025	0.016	0.009*
	Roots	234.291	156.424	77.867^{ns}	0.098	0.089	0.009^{ns}
Fe	Leaves	114.394	107.727	6.667^{ns}	0.162	0.188	0.026^{ns}
	Stem	68.636	62.424	6.212^{ns}	0.024	0.028	0.004^{ns}
	Roots	1268.485	1279.091	10.606^{ns}	0.534	0.733	0.199*

* Significant to 5% by the F test, ^{ns}: not significant.

growth of a monocotyledon such as wheat and rye (Jarvis, 1987), and eucalyptus, woody dicotyledon (Carvalho *et al*., 2003). However, for eucalyptus, Carvalho *et al*. (2003) found greater retention of Si in the roots instead of shoots after 60 days. This behavior would possibly occur in coffee plants if the experimental period were greater, since for dicotyledons it is common to find higher accumulation of Si in the roots.

According to Mitani & Ma (2005), non-accumulators species, such as tomatoes, have a lower number of Si carriers from the apoplast to the symplast and a defect in the Si carriers from cortical cells to the xylem, which explains the higher concentration of Si in the root system rather than in the shoot.

According to the classification proposed by Takahashi *et al*. (1990) and Marschner (1995), and in the experimental conditions of this study, coffee may be classified as a species that does not accumulate Si, because coffee plants have in their tissues mean levels ranging from 1.8 to 4.1 g kg^{-1} in plants grown with and without Si, respectively (Table 2). These results are similar to those found by Carvalho *et al*. (2003) in eucalyptus seedlings. These authors have concluded that although responsive to Si, eucalyptus cannot be considered an accumulator species, as most dicotyledons can.

Macronutrient contents in plants were not significantly affected by Si supply (Table 2). This was not true for micronutrients. For Zn content in roots, Cu in leaves and Mn in leaves and stem, there was significant difference among treatments. The contents of Zn in roots and Cu in leaves were greater in the treatment without Si addition, and Mn content was greater in plants grown in nutrient solution with Si addition (Table 2). Results found for Mn can be considered an effect of concentration, once the growth (greater amount of dry and fresh matter) of coffee plants was lower in the treatment with Si. For the contents of Zn and Cu, the same did not occur, given that the levels of these nutrients were higher in the treatments without Si (same treatment when there was greater plant growth).

Silva & Bohnen (2001), while working with rice grown in nutrient solution with Si, found reduced phosphorus contents in the roots when in the presence of Si. Responses in the alteration of nutrient content in plants grown in the presence of Si have also been found for dicotyledons, such as moringa (Miranda *et al*., 2002) and potato (Pulz *et al*., 2008). Silva & Bohnen (2003) found no influence of Si in macro and micronutrients content in rice grown under different concentrations of Si and Ca.

There was a higher accumulation of nutrients in the treatment without Si supply for P (leaf and stem), K (stem and roots), Ca (stem), Zn (roots), Cu (leaves), Fe (roots), and only for Mn (stem) in the treatment with Si supply (Table 2), resulting in greater plant growth (greater fresh and dry weight and total height and shoot) (Table 3). These data indicate that the addition of Si causes a reduction in coffee plant nutrient uptake with a consequent reduction in plant growth. Reduction in growth rate, as well as in nutrients, accumulation may also be associated with reduced water consumption, i.e., when perspiration rate is reduced, there is also a reduction in water consumption and obviously, a reduction in nutrient uptake, once nutrient uptake has a direct relationship with water uptake.

Accordingly, plants grown in solution with no Si addition were more efficient in the use of nutrients, given that the concept of nutritional efficiency includes the processes by which plants absorb, accumulate, and use their nutrients to produce dry matter under adequate or adverse nutrition conditions. According to Pozza *et al*. (2009) balanced nutrition with Si can reduce susceptibility to water stress and change the rhizosphere pH of plants, which occurred in this study. Even without having established physiological and nutritional function, studies indicate that Si affects the nutritional status of crops such as coffee (Santos Botelho *et al*, 2005), which was evident in this work. Pozza *et al*. (2009) when studying three varieties of coffee for Si effects, found that Si affected nutrient uptake, as well as the nutrient use efficiency of plant.

All the results for plant growth variables were significant, which indicates that the presence of Si in the nutrient solution was associated with a negative influence on such characteristics, except for the number of leaves and internodes (Table 3).

Both fresh and dry matter of stem, roots and leaves, were greater when the plants were grown in solution without Si (Table 3). These results are a consequence of the higher water consumption of plants, which led to greater plant growth. By reducing the stomatal aperture (Oliveira & Castro 2002), Si decreases the perspiration rate, with consequent reduction in water consumption (Takahashi *et al*., 1990), which could explain the higher fresh weight in plants grown in solution without Si.

Total plant height and shoot height behaved similarly to coffee plant mass accumulation (Table 3). Results found in this work for the growth in height of plants grown with Si are contrary to those observed for other crops, such as rice (Zanão Júnior *et al*., 2009) and potato (Pulz *et al*., 2008), in which Si has positively influenced their growth.

Regarding the number of leaves and internodes, there was no difference among treatments (Table 3). These results occurred because the ontogeny of plants is governed mainly by genetic factors. Even considering so, if the experimental conditions had been maintained for a longer period of time, the response of plants with regard to such characteristics could have arguably been different.

Table 3. Fresh and dry matter weight of stem, root and leaves, total plant height, shoot height, number of leaves and internodes of coffee plants grown in nutrient solution with and without silicon, at the end of 33 days

Variables	With Si	Without Si	Difference
Stem fresh weight (g plant^{-1})	1.39	1.79	0.4*
Stem dry weight (g plant^{-1})	0.35	0.45	0.1*
Root fresh weight (g plant^{-1})	3.30	4.32	1.02*
Root dry weight (g plant^{-1})	0.43	0.57	0.14*
Leaf fresh weight (g plant^{-1})	5.70	7.12	1.42*
Leaf dry weight (g plant^{-1})	1.44	1.75	0.31*
Total plant height (cm)	43.33	49.00	5.67*
Shoot height (cm)	16.44	18.00	1.56*
Number of leaves per plant	15.00	15.56	0.56^{ns}
Number of internodes per plant	6.33	6.78	0.45^{ns}

* Significant to 5% by the F test, ^{ns}: not significant.

CONCLUSION

Young coffee plants have low Si uptake rate, which preferably accumulates in leaves.

In a nutrient solution, supplementation with silicon, in the absence of stress conditions, encourages the reduction of water consumption, of potassium uptake, and of coffee plant total weight.

When coffee plants are grown in a nutrient solution supplemented with silicon, there is lower accumulation of phosphorus, potassium, calcium, zinc, copper and iron.

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