

# Silicon Supplied via Root or Leaf Relieves Potassium Deficiency Effects in Common Bean

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## Research Article

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# Abstract

Potassium (K) deficiency affects physiological performance and decreasing vegetative growth in common bean plants. However, silicon (Si) supplied via nutrient solution or foliar application may relieve nutritional stress. Thus, two experiments were carried out: initially, a test was performed to determine the best source and concentration of leaf-applied Si. Subsequently, the chosen Si source was applied via nutrient solution or via leaf to verify if it is efficient in alleviating the effects caused by K deficiency. To that end, a completely randomized 2 x 3 factorial design was used, with two levels of K: deficient (0.2 mmol L<sup>-1</sup> of K) and sufficient (6 mmol L<sup>-1</sup> of K); and Si: via nutrient solution (2 mmol L<sup>-1</sup> of Si) or foliar spray (5.4 mmol L<sup>-1</sup> of Si) and control (0 mmol L<sup>-1</sup> of Si). In the first experiment, foliar spraying with sodium silicate and stabilized potassium at a concentration of 5.4 mmol L<sup>-1</sup> was better in favoring the physiology of bean plants. In the second experiment, K deficiency without the addition of Si compromised the plant's growth. Si applied through nutrient solution or foliar spray relieved K deficiency stress, increasing chlorophylls and carotenoids content, photosynthetic activity, water use efficiency and vegetative growth.

## Introduction

Potassium deficiency in bean plants (*Phaseolus vulgaris* L.) is common worldwide, inducing chlorosis on the edges of older leaves, evolving to necrosis [1]. At this stage, the increase in reactive oxygen species degrades chlorophyll, decreasing photosynthesis and increasing transpiration, with inefficient water use [1, 2, 3].

Studies show that Si can mitigate K deficiency stress, since it raises chlorophyll and antioxidant compound (carotenoid) levels, favoring photosynthesis rates [2, 3, 4, 5] and decreasing transpiration, thereby increasing the efficiency of water use [3, 6] and raising dry matter production [5, 3].

However, information about the relationship between Si and K deficiency stress in bean plants is non-existent. A number of studies on other species indicate that supplying Si nutrient solution alleviates K deficiency in soybean [5], sorghum [2] and barley crops [7], but there are no reports on Si leaf spraying and this nutritional disorder in any species. Indeed, doubts remain regarding the best Si source and concentration for leaf spraying in bean plants.

As such, a number of questions must be answered. First and foremost is whether Si leaf spraying in bean plants is agronomically feasible depending on the source and concentration of the element. The hypothesis is that supplying Si alleviates K deficiency due to increase chlorophyll content, photosynthesis and water use efficiency of the bean plant. If so, mitigating K deficiency is more evident with the supply of Si via nutrient solution (roots) compared to foliar applications, although leaf spraying can also reduce deficiency in the plant.

The aim of this study was to determine the best Si source and concentration for foliar application, and whether supplying this source via nutrient solution is efficient in attenuating K deficiency stress in bean

plants.

## Results

### Leaf-applied Si and its effect on bean plants.

The rise in leaf-applied Si concentration increased accumulation of the element, total chlorophyll content, quantum efficiency of photosystem II and shoot dry matter of bean plants, irrespective of the source used (Fig. 1a, b, c, d).

The leaf-applied Si concentrations in the form of SiK and SiNaK sources that resulted in the maximum Si accumulation, total chlorophyll content, quantum efficiency of photosystem II and dry matter were 8.93 and 8.57; 10.36 and 10.36; 8.57 and 9.64; and 9.29 and 8.57 mmol L<sup>-1</sup> of Si, respectively (Fig. 1).

Based on the results, SiNaK was similar to SiK in terms of increasing the element in the plant, but produced better results in total chlorophyll content and quantum efficiency of photosystem II, albeit not enough to affect dry matter (Fig. 1). The use of this source at 1/10th of the concentration treated of L<sup>-1</sup> was associated with 90% of maximum dry matter production, a feasible option for leaf spraying bean plants.

### Potassium and silicon.

Cultivating bean plants in a K-deficient nutrient solution resulted in less nutrient accumulation, regardless of Si treatments and control (-Si) (Fig. 2a). Only applying SiRO treatment in bean plants grown under K deficiency increased K accumulation compared to controls (Fig. 2a). In K-deficient plants, SiRO and SiLE treatment in relation to controls raised the efficiency of the macronutrient (Fig. 2b). This indicates the beneficial effect of Si in improving K absorption and Si use efficiency, contributing to alleviating nutritional stress in the bean plant.

Potassium-deficient beans plants when compared to K-sufficient plants shows decreased Si accumulation only when the element was root supplied (Fig. 2c). The use of Si favored its accumulation in bean plants with and without K deficiency, particularly when the element was supplied via SiRO compared to SiLE (Fig. 2c).

Potassium deficiency in relation to sufficiency decreased total chlorophyll and carotenoid content in control plants (-Si) and those that received leaf-applied Si (Fig. 3a, b). However, in K-deficient plants, SiRO treatment compared to the treatments SiLE and controls (-Si) resulted in higher total chlorophyll and carotenoid content (Fig. 3a, b). In plants with sufficient K levels only SiRO treatment increased total chlorophyll and carotenoid content (Fig. 3a, b).

Bean plants cultivated in K-deficient nutrient solution exhibited chlorosis followed by necrosis on the edges of the oldest leaves. It was visually evident that this system was alleviated by supplying Si, especially in SiRO treatment (Fig. 3c).

Plants stressed by K deficiency increased electrolyte leakage (Fig. 4a), reduced photosynthesis rates (Fig. 4b), raised transpiration rates (Fig. 4c) and lowered relative water content (Fig. 4d) and water use efficiency (Fig. 4e) compared to plants with sufficient K levels. However, supplying Si, especially with SiRO treatment alleviated stress in K-deficient plants, since it raised photosynthesis, relative water content, and water use efficiency, in addition to minimizing transpiration rates and electrolyte leakage (Fig. 4a, b, c, d, e).

Beans plants cultivated in K-deficient solution reduced the leaf area (Fig. 5a), root length (Fig. 5b), root density (Fig. 5c), and root area (Fig. 5d), in addition to shoot (Fig. 5e) and root dry matter (Fig. 5f) in bean plant.

However, K-deficient plants supplied with Si by the two application methods obtained an increase in leaf area (Fig. 5a), root length (Fig. 5b), root density (Fig. 5c), and root area (Fig. 5d), as well as shoot (Fig. 5e) and root dry matter (Fig. 5f), highlighting root over leaf application. On the other hand, in plants with sufficient K levels, SiRO or SiLE only increased root density and root dry matter. These results were also obtained from photographic records (Fig. 6)

## Discussion

Leaf-applied Si was agronomically feasible due to its increase in the plant, total chlorophyll content, QEPS II and consequent rise in dry matter production, irrespective of the source of the element (Fig. 1). A similar result was observed in bean plants by [8] when Si was supplied via leaves at concentrations of 2 and 4 ml L<sup>-1</sup>. Additionally, the two leaf-applied Si sources were efficient in raising accumulation of the element for the bean crop, as also verified in research by Jafarei et al. [9] who applied 3.6 g L<sup>-1</sup> of Si via leaf of bean plants.

The SiNaK source was better at raising total chlorophyll content and the QEPS II when compared to SiK, although not sufficient to affect dry matter. This Si source stands out for exhibiting sorbitol in its composition, which provides greater stability in the solution, reducing the polymerization process of the element [10] on the leaf surface.

Bean plants cultivated in K-deficient nutrient solution (0.2 mmol L<sup>-1</sup> of K) showed lower accumulation of the nutrient when compared to plants with sufficient levels, indicating the occurrence of nutritional stress (Fig. 2a). However, when these K-deficient plants received Si, especially in SiRO treatment, they exhibited an increase in accumulated K compared to controls (-Si). This may have occurred because Si stimulated H<sup>+</sup>-ATPase activity, enzymes directly linked to K absorption by the plants [11]. This increased K accumulation in deficient plants was observed in soybean supplied with Si via nutrient solution [5]. Si supply to K-deficient plants, especially through the roots, enhanced K use efficiency by the bean plant compared to controls (Fig. 2b), due to the ability of Si to increase absorption of the element (Fig. 2a) and the physiological processes associated with biomass production.

Bean plants grown in potassium deficiency compared to sufficiency showed reduced Si accumulation only in SiRO treatment (Fig. 2c). As such, K deficiency induced less Si accumulation even in plants that received the element via nutrient solution, a finding also reported for barley plants [7].

There was greater Si accumulation in bean plants when the element was supplied via SiRO compared to SiLE, irrespective of K supply (Fig. 2c). This occurred since the Si supplied in the nutrient solution makes the element available throughout the crop cycle, whereas leaf application was only performed in four stages. Leaf-applied Si promoted increased accumulation of this element in relation to controls (-Si), in plants with and without K deficiency (Fig. 2c). This indicates that leaf spraying raised Si absorption in the bean plants, a result also found in bean [9, 12] and okra plants [13].

The K deficiency reduced total chlorophyll and carotenoid content in relation to sufficiency of the macronutrient only in controls (-Si) and in SiLE treatment (Fig. 3a, b). The cultivation of plants with low K content in the nutrient solution decreased absorption of the element, causing a decline in total chlorophyll content (Fig. 2a), a finding also reported for sorghum [2]. This occurs because of the lack of this nutrient causes oxidative stress, given the increase in reactive oxygen species and putrescine content, a compound that, when in high concentrations, becomes toxic to plants [1, 2]. Thus, K deficiency resulted in chlorosis and necrosis on the edges of the oldest leaves (Fig. 3c), as previously reported by Prado [1].

In K-deficient plants, both Si supply methods favored an increase in total chlorophyll and carotenoid content compared to controls (-Si), especially in SiRO treatment (Fig. 3a, b), a difference that is visibly apparent (Fig. 3c). The beneficial effect of Si supplied via nutrient solution in K-deficient plants on increasing chlorophyll content has also been reported for other species such as sorghum [2] and barley [7].

Potassium deficiency in bean plants, with no Si addition, increased electrolyte leakage in relation to plants with sufficient levels (Fig. 4a). This occurred because K deficiency decreased intracellular pH, raising amine oxidase activity and stimulating reactive oxygen species accumulation, which oxidizes cell membrane compounds [2]. However, both Si application methods exhibited less electrolyte leakage in K-deficient plants than in controls (-Si) (Fig. 4a). This finding is corroborated Miao et al. by [5] in soybean plants that received Si via nutrient solution. This beneficial effect of Si in reducing electrolyte leakage occurred because the element induces greater plasma membrane protection [6], possibly since it increased carotenoid content (Fig. 3b). Carotenoid is a non-enzymatic antioxidant that eliminates singlet oxygen ( $^1O_2$ ), especially toxic oxygen reactive species, which leads to lipid peroxidation, resulting in a loss of cell electrolytes [14, 15] and lipid bilayer membrane stability [16].

Plants stressed by K deficiency decreased photosynthesis rates only in control plants (-Si) (Fig. 4b). This effect is due to the fact that K deficiency decreased total chlorophyll content (Fig. 3a) and raised electrolyte leakage (Fig. 4a), a finding also reported by other authors in sorghum plants [2, 3].

The beans plants grown in K-deficient that received Si experienced a rise in photosynthesis rate in relation to controls (-Si), highlighting application of the SiRO (Fig. 4b), as observed in sorghum plants [2]. This

effect is due to the fact that SiRO treatment increased K accumulation (Fig. 2a), as well as total chlorophyll (Fig. 3a) and carotenoid content (Fig. 3b).

Potassium deficiency without adding Si increased leaf transpiration rate (Fig. 4c) and decreased control plant (-Si) relative water content (Fig. 4d), since this nutrient regulates osmosis in the plant [1, 3].

SiRO or SiLE treatment decreased foliar transpiration (Fig. 4c) and increased relative leaf water content (Fig. 4d) only in K-deficient plants in relation to controls (-Si). The beneficial effect of Si on plant relative water content was reported in K-deficient sorghum [3]. This effect is due to the formation of a silica gel layer that links cellulose to epidermal cells, minimizing water loss [6], as well as the increase in aquaporin activity, a protein associated with enhancing water transport in the plant [3].

K-deficiency also decreased water use efficiency in control plants (-Si) (Fig. 4e). This is because deficiency reduces photosynthesis (Fig. 4b) and raises the leaf transpiration rate (Fig. 4c), resulting in low water use efficiency, a fact reported for other crops such as sorghum [3] and cotton [17].

However, both Si application methods increased the efficiency of water use in K-deficient plants, particularly SiRO treatment (Fig. 4e). This beneficial effect of Si in raising water use efficiency is due to the increase in photosynthesis (Fig. 4b) and decline in transpiration rate (Fig. 4c).

K-deficiency caused a decrease in plant growth (Fig. 5a, b, c, d, f and Fig. 6). This has been widely reported in the literature, given the functions of K in plants [1], where deficiency compromises biological variables, as previously mentioned. On the other hand, both Si application methods increased plant growth variables, especially via SiRO (Fig. 5a, b, c, d, f). A similar result of increased dry matter in K-deficient plants submitted to Si application via nutrient solution was obtained in other species such as soybean [5] and sorghum [2, 3].

The benefit of Si in alleviating K deficiency can be explained by the different nutritional and physiological improvements, initiating with an increase in K accumulation (Fig. 2a) and another associated with the antioxidant action of the plant, evidenced by the rise in total chlorophyll (Fig. 3a) and carotenoid antioxidant compound content (Fig. 3b) due to the decline in electrolyte leakage (Fig. 4a), favoring the photosynthesis rate (Fig. 4b). Si also maintained water in the plant, given the decrease in transpiration rate (Fig. 4c), which favored a rise in water content (Fig. 4d) and, in turn, water use efficiency (Fig. 4e). Thus, the plant physiology and nutrition improvement with the Si supply to the K deficient plant increased the efficiency of the macronutrient use to convert it in biomass (Fig. 2b), hence in the plant growth. The beneficial effects of Si applied via root on physiology and growth in K-deficient plants were also reported [2, 3, 5].

It is important to underscore that SiLE improved the growth variables of K-deficient plants when compared to controls (-Si). This may be due to the effect of leaf Si in relation to controls (-Si) in raising total chlorophyll and carotenoid content as well as photosynthesis and water use efficiency. The benefits of leaf-applied Si in alleviating K deficiency in bean plants have not been reported in the literature, since

existing studies supplied the element only via nutrient solution. The present study demonstrates the mitigating effect of Si on K deficiency, especially supplied via nutrient solution, but leaf application is a feasible alternative in bean plants.

Finally, in K-sufficient plants, SiRO or SiLE treatments had little effect on plant growth, since only root density and dry matter increased. As such, the present study showed that the most important role of Si is when plants are under nutritional stress in relation to those with sufficient levels.

## Materials And Methods

### Local and growing conditions.

Two experiments were conducted in a hydroponic growing system in the greenhouse at the School of Agricultural and Veterinarian Sciences (UNESP), Jaboticabal, Brazil.

Seeds of common beans (cv. BRS Estilo) were obtained from the Brazilian Agricultural Research Corporation of the Ministry of Agriculture, Livestock and Food Supply, Brazil.

The use of plant parts in the present study complies with international, national, and/or institutional guidelines. This research was not conducted with endangered species and was conducted in accordance with the is in accordance with the Declaration of IUCN Policy on Research Involving Endangered Species.

The first experiment was carried out to obtain the best Si concentration and source for Si leaf spraying, which occurred between August and the end of the crop cycle, which lasted 115 DAE (days after emergence). Based on results of the first experiment, a second experiment was conducted to evaluate the effect of Si on the physiology and dry matter yield of common beans plants under K deficiency, starting in December and maintained until the emergence of K deficiency symptoms, corresponding to the phenological stage R5 (28 DAE).

The relative air humidity and maximum and minimum temperature were recorded throughout the experimental period. There was a high variation in the average relative humidity ( $34.39 \pm 9\%$  |  $32.79 \pm 8\%$ ), minimum temperature ( $17.9 \pm 7^\circ\text{C}$  |  $19.47 \pm 5^\circ\text{C}$ ) and maximum temperature ( $44.8 \pm 8^\circ\text{C}$  |  $38.56 \pm 7^\circ\text{C}$ ) to the first and second experiment respectively. High temperatures may have induced plants to possible stresses, considering that the average temperature for optimum beans crop growth is between 18 and  $24^\circ\text{C}$  [18].

### Growing conditions.

For the first experiment, the seeds were sown in a trays. Then the seedlings at five DAE were transplanted to  $7 \text{ dm}^3$  polypropylene pots (upper diameter: 16 cm; lower diameter: 11 cm; height: 33 cm), filled with  $6 \text{ dm}^3$  medium texture sand, previously washed with water, 1% HCl solution and deionized water, maintaining two plants per pots. These were irrigated daily with nutritive solution applied in order to maintain 70% water-holding capacity in the substrate.

For the second experiment, the seeds were also sown in trays, and the seedlings at five DAE were transplanted to polypropylene pots (length: 44 cm; width: 19 cm and height: 14 cm, with capacity for 10 liters), also filled with the nutritive solution.

The nutrient solution used in both experiments was proposed by Hoagland and Arnon [19]. The solution concentration during the first and second week of the growing season was maintained at 10 and 25%, respectively. From the third week until the end of the experiments, the concentration was raised to 50%. The pH value of nutritive solution was maintained between 5.5 and 6.5, adjusted using NaOH ( $1 \text{ mmol L}^{-1}$ ) and HCl ( $1 \text{ mmol L}^{-1}$ ) solution. In the second experiment, the hydroponic solution was modified with different levels of K, as per the treatment (Table 1), and renewed every week to replace the water, Si and nutrients absorbed by the plants.

Table 1  
Amount of K provided and adjustment between control (-Si), Si via roots (SiRO) and Si via leaf spraying (SiLE) treatments in the second experiment.

K supply route	-K			+K		
	-Si	SiRO	SiLE	-Si	SiRO	SiLE
	-----mmol L <sup>-1</sup> -----					
Via root	0.2	*	0.2	6	5.8*	6
Via leaf	0.5	0.5	**	0.5	0.5	**
Total K	0.7	0.7	0.7	6.5	6.5	6.5
* received 0.2 mmol K via SiNaK; ** received 0.5 mmol via SiNaK						

### Experimental design.

The first experiment was carried out in a randomized complete block design in a 2 x 4 factorial scheme, with two Si sources: sodium and potassium silicate stabilized with sorbitol (SiNaK) ( $113.4 \text{ g L}^{-1}$  of Si and  $18.9 \text{ g L}^{-1}$  of  $\text{K}_2\text{O}$ , pH 11.8) and potassium silicate without stabilizer (SiK) ( $128 \text{ g L}^{-1}$  of Si and  $126 \text{ g L}^{-1}$  of  $\text{K}_2\text{O}$ , pH 12.0). Four concentrations: 0.0; 5.4; 10.8 and  $16.2 \text{ mmol L}^{-1}$  of Si. All treatments were conducted with four replicates.

The second experiment was arranged in completely randomized blocks in a 2 x 3 factorial scheme, with two concentrations of K in the nutrient solution: deficient (-K) ( $0.2 \text{ mmol L}^{-1}$  of K) and sufficient (+K) ( $6 \text{ mmol L}^{-1}$  of K), and two modes of Si supply: roots via nutrient solution (SiRO) ( $2 \text{ mmol L}^{-1}$  of Si), leaves (SiLE) ( $5.4 \text{ mmol L}^{-1}$  of Si per application) and control (-Si) ( $0 \text{ mmol L}^{-1}$  of Si), in four repetitions.

### Si application and K adjustment.

For the first experiment, foliar Si applications (SiNaK and SiK) were performed in three stages of development: V4 (emergence of the 3rd trifoliolate leaf), R6 (flowering – opening of the first flower) and R7 (pod formation). The volume of the solution applied varied according to plant size and 8, 16 and 24 ml of the solution were sprayed in stages V4, R6 and R7 respectively.

For the second experiment, SiNaK was applied as a Si source. In the SiRO treatment, the Si supply via root was performed in a nutrient solution throughout the experiment.

To perform the foliar application in the second experiment (SiLE treatment), a solution with a concentration of  $5.4 \text{ mmol L}^{-1}$  of Si (SiNaK) was made and, then, the application to the leaves was carried out manually. The volume of Si solution applied increased according to plant size, with 0.56; 0.84; 1.12 and 1.40 ml of the silicate solution per plant for the first, second, third, and fourth spraying, respectively, at 8, 13, 18 and 23 DAE.

The solutions used for leaf spraying in both experiments were adjusted with a solution of NaOH and HCl to maintain a pH of  $6.0 \pm 0.2$ . Silicon was applied to the leaves immediately after solution preparation.

The SiNaK and SiK sources contains K in its composition, after Si sprayings, foliar applications were performed with potassium chloride (KCl) to balance the K of the treatments. In the second experiment, the K provided by the SiNaK source was also adjusted for the root supply (Table 1).

It is important to highlight that  $0.7 \text{ mmol L}^{-1}$  of K from SiNaK does not meet the demand of  $6 \text{ mmol L}^{-1}$  suggested by Hoagland and Arnon [19] to supply K to plants, and nutrient deficiency of this nutrient is expected.

Temperature ( $^{\circ}\text{C}$ ) and relative humidity (%) in both experiments were measured during the foliar applications, obtaining values between 9 and  $22^{\circ}\text{C}$  and 60 and 80% respectively.

### **Plant analysis.**

In the first experiment, assessments were conducted in stage R7, and at twenty five DAE for the second experiment, both in the upper third of the trifoliolate leaf.

*Quantum efficiency of photosystem II and Gas exchange parameters.* In the first experiment, the quantum efficiency of photosystem II (QEPII) was measured with a fluorimeter (Opti-Science®-Os30P+).

In the second experiment, Gas exchange parameters were determined between 9:00–11:00 a.m, using four replicates for each treatment. Photosynthetic rate and transpiration rate were measured using an open infrared gas analyser (IRGA LcPro-SD, ADC BioScientific Ltd., Hoddesdon, Reino Unido). The IRGA chamber was irradiated with a photosynthetic photon flux density of  $1200 \mu\text{mol m}^{-2} \text{ s}^{-1}$  and under ambient  $\text{CO}_2$  concentration ( $400 \pm 10 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ). Water use efficiency (WUE) was calculated as net photosynthetic rate (A) per transpiration rate (E):  $\text{WUE} = \text{A}/\text{E}$ .

*Total chlorophyll and carotenoid content.* Total chlorophyll (a + b) and carotenoid content in the first and second experiment were measured by an absorbance spectrophotometer at 663 nm for chlorophyll a, 647 nm for chlorophyll b, and 470 nm for carotenoids. Pigments concentrations were determined following the methodology of Lichtenthaler and Wellburn [20].

*Electrolyte leakage and relative water content.* In the second experiment, the electrolyte leakage index and relative water content (RWC) were measured according to the methodology proposed by Dionisio-Sese and Tobita [21] and González and González-Vilar [22], respectively.

*Plant growth analysis and dry matter.* Leaf area of the plant was measured with a LI – 3100 Area Meter®. Moreover, the root system was analyzed using the Delta-TScan system and the length measured using the method developed by Harris and Campbell [23]. Root density was calculated by the ratio between root length and solution volume in the pot.

The plants were cut and separated into shoots and roots. Next, the samples were washed with deionized water, 0.1% detergent solution, 0.3% HCl solution and again with deionized water, and dried in a forced air oven at a temperature of  $65^{\circ}\text{C} \pm 5$ , until reaching constant weight. After drying, root and shoot dry matter were obtained, followed by grinding in a Wiley mill.

*Si accumulation and K use efficiency.* To determine the Si content, shoot dry matter (first experiment) and shoot and root dry matter (second experiment) were used. For Si analysis, the samples were extracted following the methodology proposed by Kraska and Breitenbeck [24], and measured in a spectrophotometer at 410 nm to obtain Si content, following the methodology described by Korndörfer et al. [25].

In the second experiment, K content was analyzed by digestion in nitric perchloric acid solution, followed by atomic absorption spectrophotometer reading according to the methodology described by Zasoski and Burau [26]. K use efficiency was estimated considering the dry matter production and K content, according to the methodology described by Siddiqi and Glass [27]:  $(\text{total dry matter production})^2 / (\text{total nutrient content in the plant})$ .

Based on Si, K and dry matter values, the accumulation of these elements in the entire plant (shoots and roots) was calculated following the formula:  $\text{Element accumulation} = ((\text{element content g kg}^{-1}) * (\text{plant mass g per plant}))/1000$ .

### **Statistical analysis.**

Experimental data were submitted to analysis of variance applying the F-test, and when significant for qualitative variables, to Tukey's test ( $p < 0.05$ ) to compare the means, using SAS statistical software 9.2 [28].

## **Conclusions**

Leaf spraying with Si was agronomically feasible for bean plants, particularly silicate of sodium and potassium stabilized at a concentration of  $5.4 \text{ mmol L}^{-1}$ .

Si supplied via nutrient solution or leaf application mitigated K-deficiency stress in the bean plant due to improvements in nutritional, physiological and growth variables, underscoring Si supply via nutrient solution compared to leaf application, although the latter also exhibited attenuating properties.

## Declarations

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### Author contributions

M.M.S.S. conducted the experiments and wrote the manuscript, being responsible for the analysis in general. R.M.P., J.P.S.J and G.C.M.T. contributed to the manuscript writing. J.C.S.D. contributed to the analysis of data and creation of graphs. R.L.S.M. collected the data.

All authors contributed to the revision of the manuscript.

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### Competing interests

The authors declare no competing interests.

### Additional information

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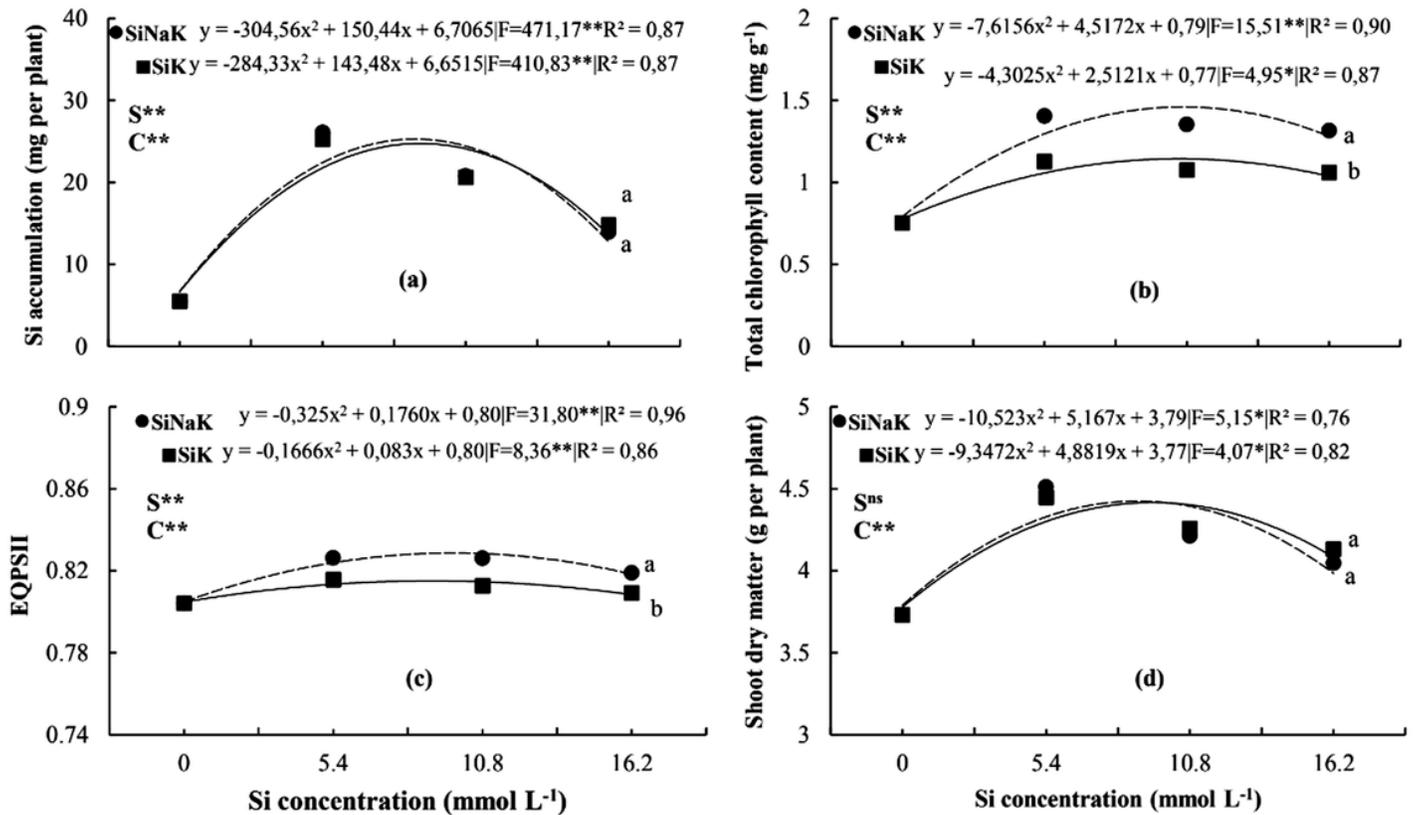
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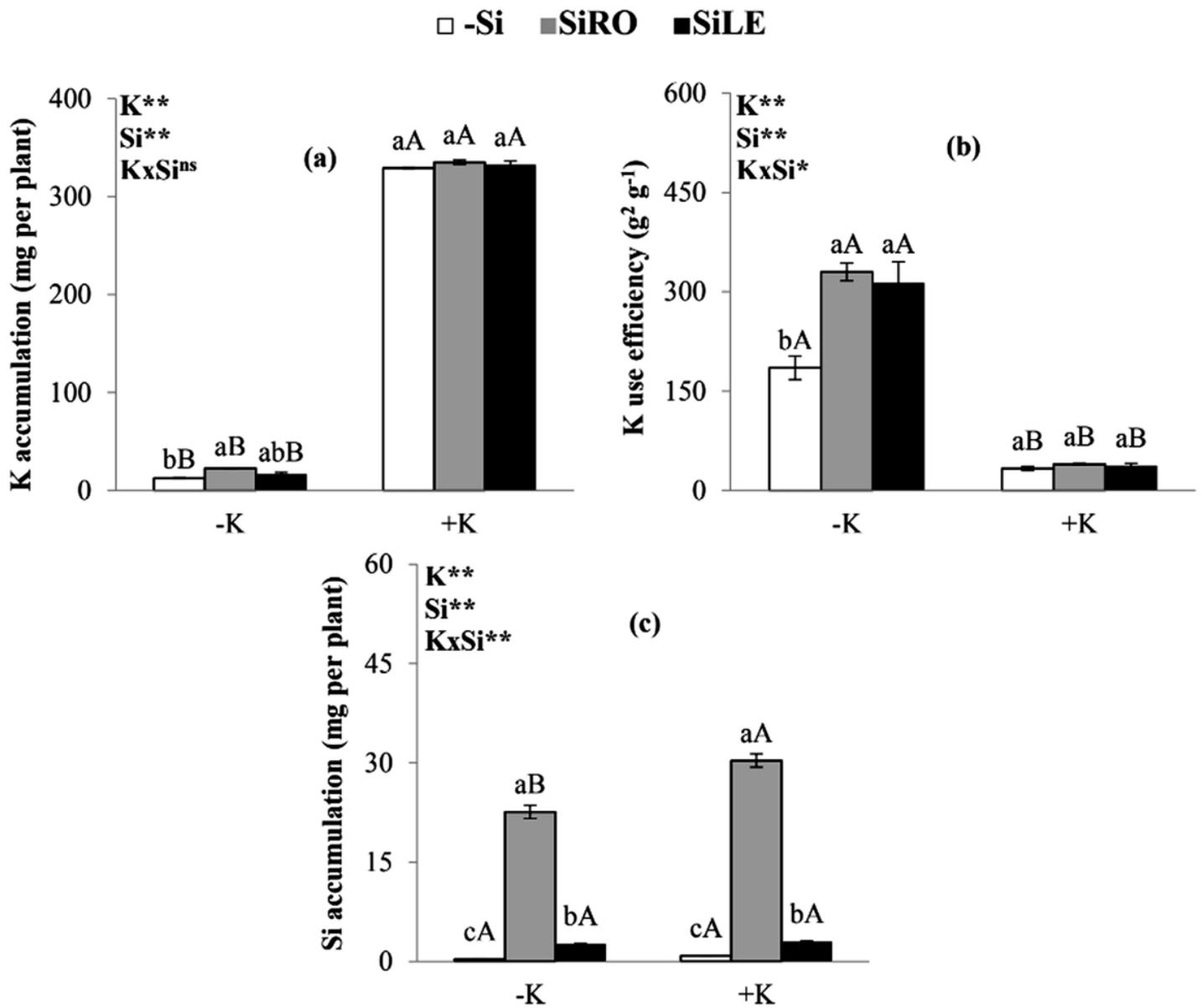
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## Figures



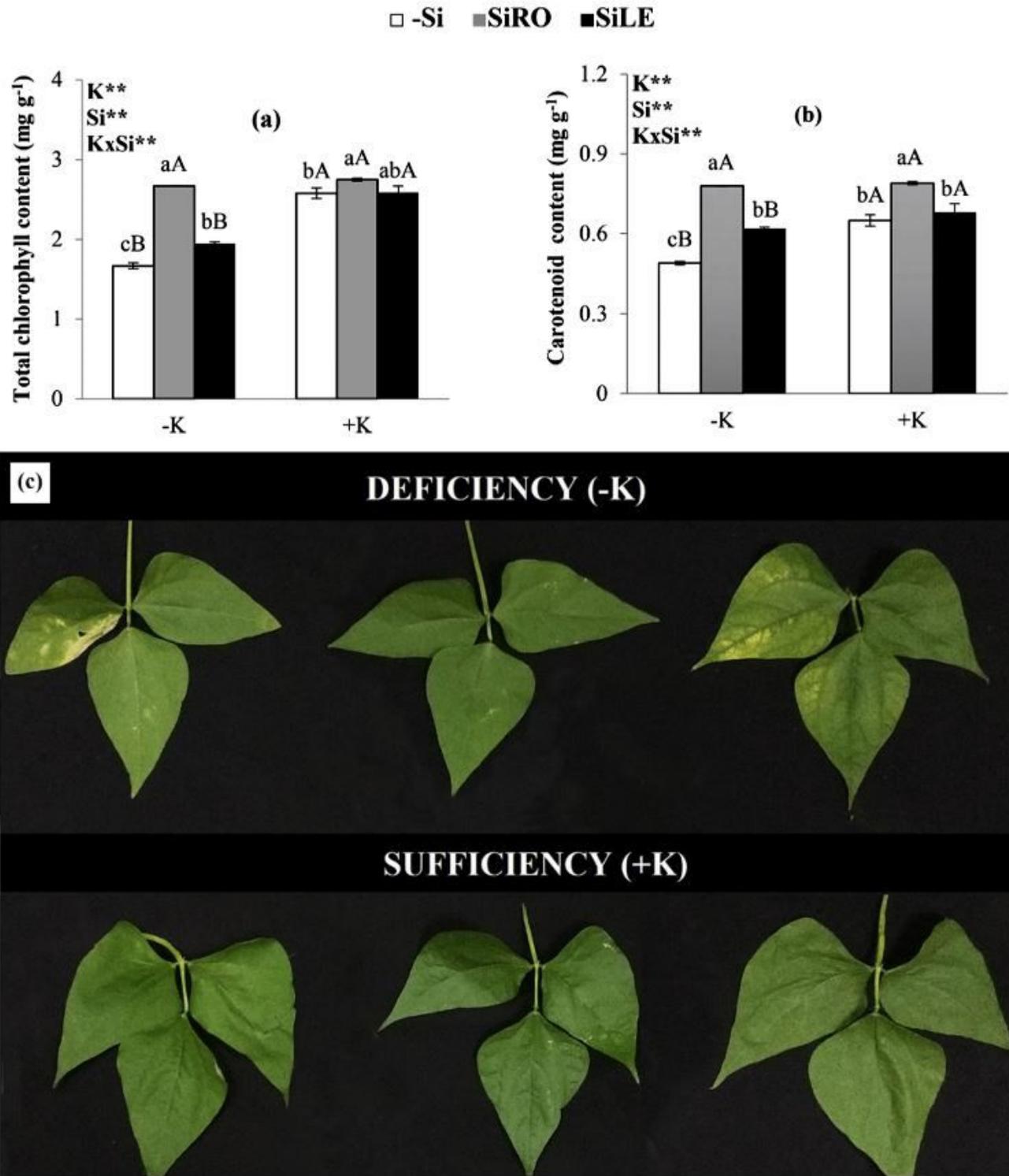
**Figure 1**

Si accumulation (shoot) (a), total chlorophyll content (b), QEPII – Quantum efficiency of photosystem II (c) and shoot dry matter (d) of bean plants cultivated with different sources (S) of Si [sodium and potassium silicate stabilized (SiNaK) and potassium silicate without stabilizer (SiK)] and increasing concentrations (C) of leaf-applied Si. \*\*Significant at 1% probability; ns no significant at 5% probability; Different letters in the same Si concentration indicate differences ( $P < 0.05$ , Tukey test) between treatments.



**Figure 2**

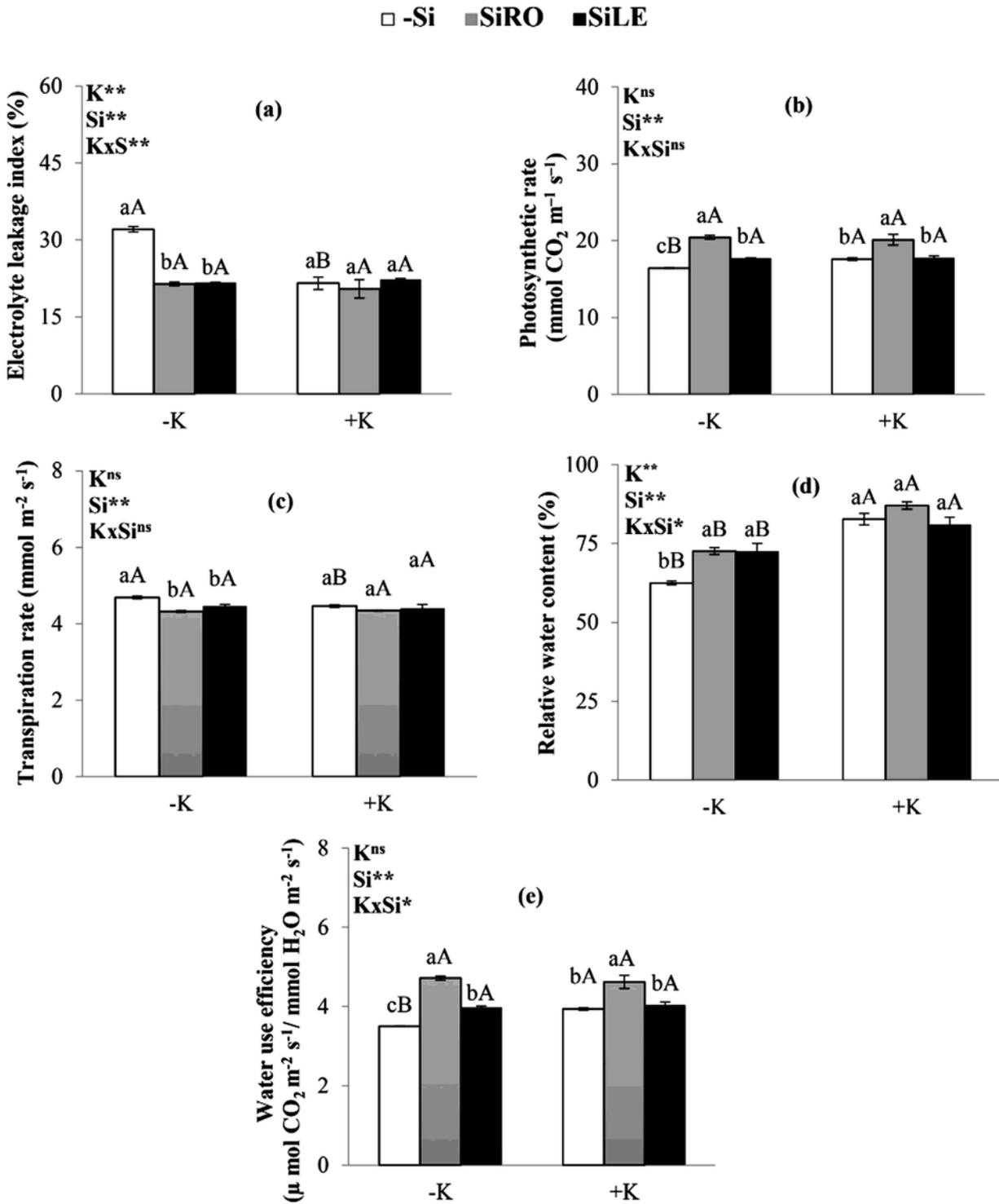
K accumulation (shoot + root) (a), K use efficiency (b) and Si accumulation (shoot + root) (c) of bean plants cultivated in a hydroponic system under deficiency (-K) and sufficiency (+K) of K, with Si supplied via nutrient solution (root) (SiRO), leaf spraying (SiLE), and control (-Si). The error bars in the figures represent standard error. Different letters, lower case between the supply of Si in the same concentration of K, and upper case between concentrations of K in the same form of supply of Si, indicate differences ( $P < 0.05$ , Tukey's test) between treatments.



**Figure 3**

Total chlorophyll content (a), carotenoid content (b) and chlorosis in oldest leaves (c) of bean plants cultivated in a hydroponic system under deficiency (-K) and sufficiency (+K) of K, with Si supplied via nutrient solution (root) (SiRO), leaf spraying (SiLE), and control (-Si). The error bars in the figures represent standard error. Different letters, lower case between the supply of Si in the same concentration

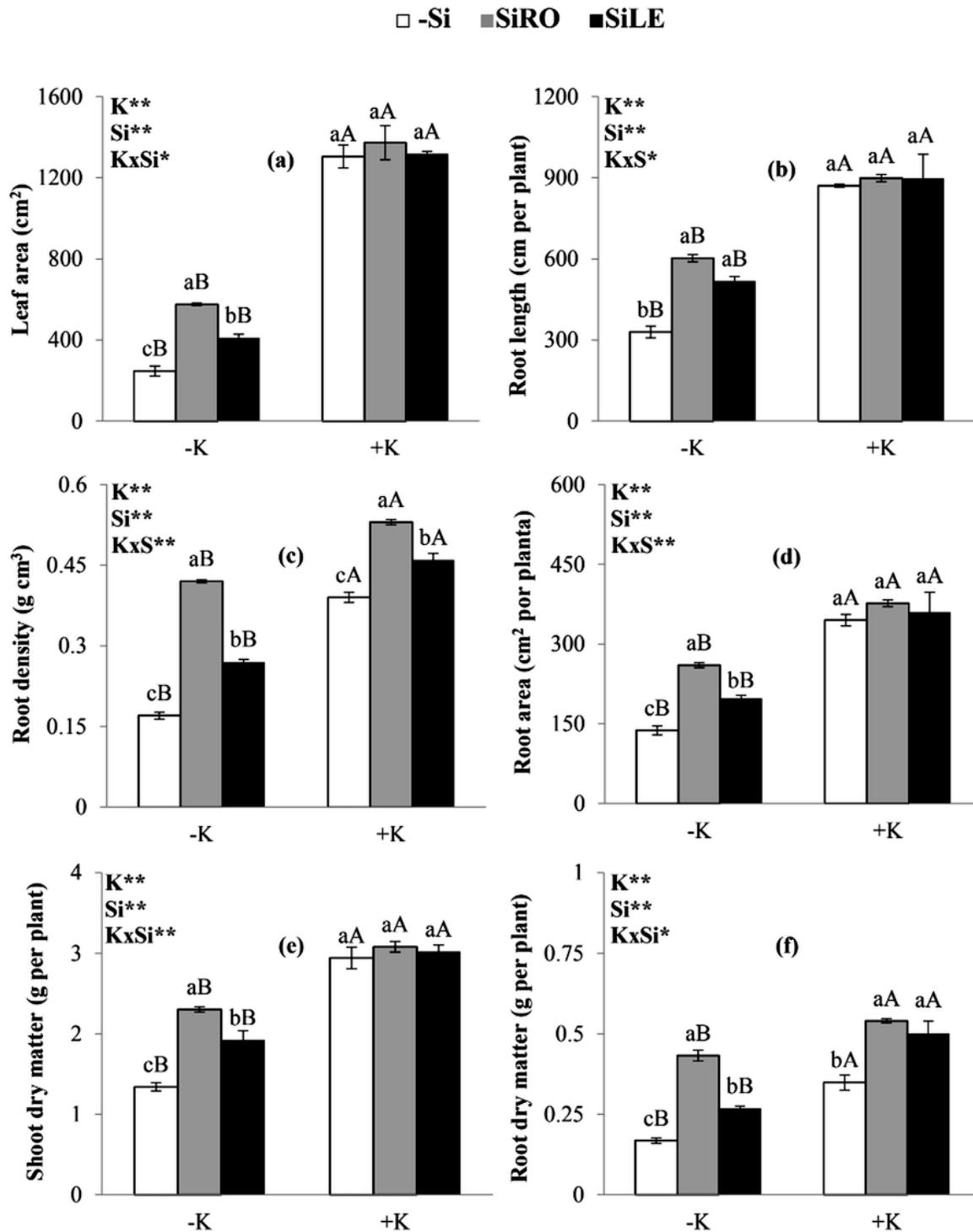
of K, and upper case between concentrations of K in the same form of supply of Si, indicate differences ( $P < 0.05$ , Tukey's test) between treatments.



**Figure 4**

Electrolyte leakage index (a), photosynthetic rate (b), transpiration rate (c), relative water content (d) and water use efficiency (e) of bean plants cultivated in a hydroponic system under deficiency (-K) and sufficiency (+K) of K, with Si supplied via nutrient solution (root) (SiRO), leaf spraying (SiLE), and control

(-Si). The error bars in the figures represent standard error. Different letters, lower case between the supply of Si in the same concentration of K, and upper case between concentrations of K in the same form of supply of Si, indicate differences ( $P < 0.05$ , Tukey's test) between treatments.



**Figure 5**

Leaf area (a), root length (b), root density (c), root area (d), shoot dry matter (e) and root dry matter (f) of bean plants cultivated in a hydroponic system under deficiency (-K) and sufficiency (+K) of K, with Si

supplied via nutrient solution (root) (SiRO), leaf spraying (SiLE), and control (-Si). The error bars in the figures represent standard error. Different letters, lower case between the supply of Si in the same concentration of K, and upper case between concentrations of K in the same form of supply of Si, indicate differences ( $P < 0.05$ , Tukey's test) between treatments.



Figure 6

Si effect on shoot and root growth of bean plants cultivated in a hydroponic system under deficiency (-K) and sufficiency (+K) of K, with Si supplied via nutrient solution (root) (SiRO), leaf spraying (SiLE), and control (-Si).