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Effect of Foliar Silicon Application on Nutrient Content in Early Crop Potato Tubers

Wanda Wadas

Institute of Agriculture and Horticulture, Siedlce University of Natural Science and Humanities, B. Prusa 14, 08-110 Siedlce, Poland; wanda.wadas@uph.edu.pl

Abstract: As some trace elements can enhance plant nutrient uptake and assimilation, it was hypothesized that foliar silicon application could enhance nutrient content in early-crop potato tubers. The effect of dosage (23.25 g Si·ha^{-1} or 46.50 g Si·ha^{-1}) and time (the leaf development stage—BBCH 14–16, tuber initiation stage—BBCH 40–41, at both the leaf development stage and tuber initiation stage) of the silicon application on the nutrient contents in early crop potato tubers was investigated. Silicon had no effect on the potassium (K), phosphorus (P), calcium (Ca), or magnesium (Mg) contents in potato tubers, but it reduced sodium (Na) accumulation, especially under water deficit conditions during tuber bulking. This resulted in a reduction in the mass ratios of Na^+/Ca^{2+} and Na^+/Mg^{2+} in tubers. Silicon dosage significantly affected the Na accumulation by potato tubers only in the warm and very dry growing season. Under drought stress, silicon at 46.50 g Si·ha^{-1} reduced the Na content in potato tubers more than at 23.25 g Si·ha^{-1}. Under periodic water deficits, the time of silicon application affected the Na accumulation by potato tubers more than the silicon dosage. The Na content in tubers was the highest with two silicon applications. Although silicon reduced the Na accumulation, the ratio of the sum of univalent cations to the sum of bivalent cations $(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$ in tubers was at the same level, both in cultivations with and without silicon.

Keywords: sodium metasilicate; new potatoes; macronutrients; ionic ratios

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1. Introduction

Potato tubers contain 1.0–1.2% of minerals. Potassium (K) is the basic mineral in potatoes. Phosphorus (P) and magnesium (Mg) are present in potato tubers in moderate quantities, while calcium (Ca) is present in small quantities [1,2]. Potatoes are an important source of minerals in the human diet. The mineral content in potato tubers depends on the cultivar and maturity stage and is affected by growth conditions, i.e., soil type, weather, and cultivation system [3–6].

The mineral content of potato tubers is largely determined by the phytoavailability of the mineral elements in the soil. The use of some trace elements can enhance plant nutrient uptake and assimilation [7,8]. Although silicon (Si) is a non-essential nutrient for plants, it is classified as a beneficial element for plant growth and evolving as a biostimulant or fertilizer, improving plant growth and abiotic stress tolerance (especially in silicon accumulating plant species) when properly employed. Silicon mitigates environmental stresses in plants by regulating the physiological, biochemical and molecular responses. It can influence water relations and nutrient uptake and mobility inside the plant, increase the photosynthesis rate, regulate the activities of certain enzymes and reduce oxidative stress, and regulate gene expression related to stress tolerance [9–13]. The recent progress of research on the role of silicon as a nutrient suggests an increase in the use of Si-based fertilizers in sustainable crop production [12–14]. According to Yan et al. [15], sodium silicate and potassium silicate are only two forms of water-soluble silicate that can be used as a foliar fertilizer. With the development of nanotechnology, silicon application in nano-fertilizers has been gaining increasing importance [13,14]. Studies showed the regulatory role of silicon in mitigating plant nutritional stress and the interaction of silicon with essential and beneficial elements in plants [9,10,14,16]. The exogenous application of silicon (to soil or foliar) facilitates the direct uptake of silicon by plants and helps in the uptake of other essential nutrients [11]. The possible mechanisms for Si-induced nutrient uptake include increasing water uptake and transpirational driving forces, thus enhancing mineral nutrient movement from the soil into the roots; enhancing ion mobilization in roots; stimulating membrane H^+-ATPase activity during nutrient uptake; regulating ion transporter genes and enhancing the translocation of metabolites that contribute to root/shoot ion transport [17]. The meta-analysis showed changes in the uptake of some elements when stressed plants are supplied with silicon. Metal concentration was not generally reduced, while sodium (Na) concentration was reduced [18]. Under drought stress, silicon improved macronutrient accumulation by several agricultural and horticultural plants, including rice, wheat, maize, sunflower and some grass species [10], sugar beet [19], cucumber [20] and melon [21]. To date, few studies have focused on the effect of silicon on the mineral content in potato tubers. A greenhouse pot experiment in Iran showed that silicon (nano-silica, sodium silicate, nano-clay, and Bentonite) application increased the K and P contents and decreased Mg content in mini-tubers of late potato cultivar [22]. A one-year field experiment in Iran showed that foliar application of silicon (silica (SiO_2) or sodium silicate nanoparticles (Nano-$NaSiO_3$)) increased the K content in leaves of late potato cultivar under salinity stress and reduced the Na^+/K^+ ratio [23]. Another one-year field experiment in Poland showed that foliar application of silicon (orthosilicic acid (H_4SiO_4) had no effect on K, P, Ca, or Mg content in tubers of medium-late potato cultivar [24].

Silicon application is interesting as a low-input environmentally friendly cropping management tool in sustainable potato production; however, the literature data on the silicon effect on nutrient content in potato tubers are relatively limited, especially in early crop potatoes. Potatoes as a staple food in many countries are an important source of minerals in the human diet. The current study aimed to determine the effect of foliar silicon application on the macronutrient contents in early crop potato tubers and their ionic ratios. In the study, it was hypothesized that foliar silicon application could contribute to enhancing mineral contents in potato tubers. Likewise, it was assumed that the potato response to foliar silicon application depends on the dosage and time of application.

2. Materials and Methods

2.1. Plant Material and Experimental Design

The field experiment was carried out in central-eastern Poland over three growing seasons (2016–2018). The experiment was performed on Haplic Luvisol (LV-ha) with a sandy loam texture, with an acidic–slightly-acid reaction, high content of available P, medium–high content of K, and a low–medium content of Mg (Table 1). Soil samples were taken from the plowing level (0–20 cm) in autumn. The soil chemical properties were determined using soil laboratory procedures at the National Chemical and Agricultural Station: organic matter with Turin's method, pH with a potentiometric method in 1 M KCl solution, available forms of phosphorus with a spectrophotometric method, potassium with the flame atomic emission spectroscopy (FAES) method and magnesium with the flame atomic absorption spectroscopy (FAAS) method.

The hydrothermal conditions during the potato growth period were different (Table 2). The year 2016 was warm, with periodic water deficits, during potato growth. The year 2017 was warm and moderately wet, whereas 2018 was warm and very dry. The favorable thermal and moisture conditions for early potato production were in 2017. In 2016 and 2018 there were water deficits during tuber bulking. In 2016, the total precipitation in June was over 40% lower than the long-term average. In 2018, the total precipitation in May and June was two times lower than the long-term average.

Table 1. Soil chemical properties at the experimental site.

Soil Chemical Properties	Years		
	2016	**2017**	**2018**
Organic Matter; %	1.49	1.59	1.34
Soil pH_{KCl}	5.5	5.7	5.2
Available Nutrients; mg·kg^{-1}			
P	102	114	97
K	95	124	93
Mg	42	35	23

Table 2. Mean air temperature and precipitation total in the potato growing period.

Year	Months		
	April	**May**	**June**
	Mean air temperature; °C		
2016	9.1	15.1	18.4
2017	6.9	13.9	17.8
2018	13.1	17.0	18.3
Many year (1981–2010)	8.3	12.2	16.8
	Precipitation total; mm		
2016	28.7	54.8	36.9
2017	59.6	49.5	57.9
2018	34.5	27.3	31.5
Many year (1981–2010)	41.2	53.0	63.8

The effect of dosage and time of silicon (Si) application on the macronutrient content in early crop potato tubers was determined. The source of silicon was the liquid plant growth stimulant Optysil (Intermag Ltd., Olkusz, Poland). Optysil contains 93 g Si (7.8 m/m) and 24 g Fe (2 m/m) in 1 dm^{-3}, in the form of sodium metasilicate (Na_2SiO_3) and iron chelate (Fe-EDTA).

The field experiment was established as a two-factor (2 × 3) split-plot design with a control object without silicon, with three replications. The main plots were silicon dosage: 23.25 g Si·ha^{-1} (0.25 dm^3·ha^{-1} of Optysil) and 46.50 g Si·ha^{-1} (0.50 dm^3·ha^{-1} of Optysil), and the subplot times of silicon application: in the leaf development stage (under the terms of uniform codes of phenologically similar growth stages of plant species [25], BBCH 14–16 stage), tuber initiation stage (BBCH 40–41), or in both leaf development stage and tuber initiation stage (BBCH 14–16 and BBCH 40–41). Potato plants sprayed with water were used as a control. A single plot control was located between the main plots.

The drought-sensitive very early potato cultivar Catania (Europlant Pflanzenzucht GmbH, Lüneburg, Germany) registered in the Common Catalogue of Varieties of Agricultural Plant Species (CCA) was grown. It is one of the most widely grown very early potato cultivars in central-eastern Poland, with a cream-white flesh and multi-purpose cooking type (B). Potato cultivation was carried out according to common agronomical practices. Farmyard manure was applied in autumn at a rate of 25 t·ha^{-1}, and mineral fertilizers were applied at rates of 80 kg N (ammonium nitrate), 35 kg P (superphosphate), and 100 kg K (potassium sulfate) per hectare in spring. Six-week pre-sprouted seed potatoes were planted on 6 April 2016, 10 April 2017, and 9 April 2018. The plot area was 16.2 m^2 (96 plants per plot). Colorado potato beetle (*Leptinotarsa decemlineata*) was controlled using thiamethoxam (Actara 25 WG; Syngenta Crop Protection AG, Basel, Switzerland). Potatoes were harvested 75 days after planting on 21 June 2016, 26 June 2017, and 25 June 2018.

Laboratory studies were conducted on samples of 50 different-sized tubers taken from each plot. Potato tubers were analyzed for the content of P, K, Ca, Mg and Na with the inductively coupled plasma-optical emission spectroscopy (ICP–OES) method (Optima 8300, Perkin Elmer, Boston, MA, USA) after sample mineralization in HNO_3 in a microwave digestion system (Ethos Plus, Milestone, Sorisole, Italy). The contents of macronutrients were expressed as grams per kilogram of potato tuber dry matter (DM). The ionic (mass) ratios of K^+/Ca^{2+}, K^+/Mg^{2+}, Na^+/Ca^{2+}, Na^+/Mg^{2+}, $(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$ and Ca/P were calculated.

2.2. Statistical Analysis

The results of the three-year study were analyzed statistically using a two-factor analysis of variance (ANOVA) for the split-plot design (silicon dosage × time of silicon application × year), with a control object. The analysis of the results of the study was conducted using the orthogonal contrast to compare the control, without silicon, with the test objects treated with silicon. The significance of orthogonal contrast was tested on the basis of the error resulting from the interaction of this contrast with the replications. The significance of sources of variability was tested using the *F* Fisher-Snedecor test, and the differences between the compared averages were verified using Tukey's test ($p \leq 0.05$).

3. Results

3.1. Macronutrient Contents

Silicon (Si) did not affect the content of K, P, Ca, or Mg in potato tubers but reduced the Na content (Table 3). Following the application of silicon, the Na content in tubers was lower, on average, by 0.058 $g \cdot kg^{-1}$ DM (over the three-year period), compared with the control treatment without silicon.

Table 3. Effect of silicon (Si) on macronutrient content in potato tubers.

Treatment	Year			Mean
	2016	2017	2018	
Potassium (K); $g \cdot kg^{-1}$ dry matter (DM)				
Control	19.47 a	20.27 a	18.65 a	19.46 a
With Si	19.64 a	21.16 a	19.14 a	19.98 a
Phosphorus (P); $g \cdot kg^{-1}$ DM				
Control	2.194 a	1.709 a	2.240 a	2.048 a
With Si	2.118 a	1.814 a	2.221 a	2.051 a
Magnesium (Mg); $g \cdot kg^{-1}$ DM				
Control	0.886 a	0.709 a	0.730 a	0.775 a
With Si	0.898 a	0.718 a	0.708 a	0.774 a
Calcium (Ca); $g \cdot kg^{-1}$ DM				
Control	0.256 a	0.286 a	0.220 a	0.254 a
With Si	0.241 a	0.266 a	0.224 a	0.244 a
Sodium (Na); $g \cdot kg^{-1}$ DM				
Control	0.399 a	0.415 a	0.387 a	0.400 a
With Si	0.311 b	0.391 a	0.325 b	0.342 b

Means within columns for each data type followed by the same letters do not differ significantly at $p \leq 0.05$.

The effect of silicon depended on the weather conditions during potato growth. Silicon significantly affected Na accumulation by potato tubers in 2016 and 2018, with drought periods during tuber bulking. In the warm growing season in 2016, with periodic water deficits, following the application of silicon, the Na content in tubers was lower, on average, by 0.088 $g \cdot kg^{-1}$ DM, compared with the control treatment without silicon. In the warmer and very dry growing season of 2018, silicon reduced the Na content in tubers, on average, by 0.062 $g \cdot kg^{-1}$ DM.

The study demonstrated the significant effect of the interaction of the years and the dosage of silicon and the interaction of the years and the time of silicon application on Na accumulation by potato tubers (Table 4). The silicon dosage had a significant effect on the Na content in tubers only in the very dry growing season of 2018. In that year, the Na content in tubers was higher after the application of 23.25 g Si·ha^{-1} (0.25 dm^3·ha^{-1} of Optysil). The time of silicon application had a significant effect on the Na content in tubers in 2016, with periodic water deficits during potato growth. Regardless of silicon dosage, in 2016, the Na content in tubers was the highest with two silicon applications, first in the leaf development stage, and with repeated treatment in the tuber initiation stage (BBCH 14–16 and BBCH 40–41).

Table 4. Effect of dosage and time of silicon (Si) application on sodium (Na) content in potato tubers; g·kg^{-1} DM.

Dosage and Time of Silicon Application	Year			Mean
	2016	2017	2018	
Silicon dosage				
23.25 g Si·ha^{-1}	0.317 a	0.390 a	0.345 a	0.351 a
46.50 g Si·ha^{-1}	0.306 a	0.391 a	0.306 b	0.334 a
Time of silicon application				
BBCH 14–16	0.314 ab	0.401 a	0.312 a	0.342 a
BBCH 40–41	0.288 b	0.379 a	0.332 a	0.333 a
BBCH 14–16 and BBCH 40–41	0.332 a	0.393 a	0.332 a	0.352 a

Time of silicon application: leaf development stage, BBCH 14–16; tuber initiation stage, BBCH 40–41; both leaf development stage and tuber initiation stage, BBCH 14–16 and BBCH 40–41. Means within columns for each data type followed by the same letters do not differ significantly at $p \leq 0.05$.

The study demonstrated the significant effect of the interaction of year, dosage and time of silicon application on Na accumulation by potato tubers (Figure 1). In 2016, with periodic water deficits, the Na content in tubers was the highest after the application of 23.25 g Si·ha^{-1} at the leaf development stage and with repeated treatment at the tuber initiation stage with the same dose of silicon. In the very dry year 2018, the Na content in tubers was the highest after the application of 23.25 g Si·ha^{-1} at the tuber initiation stage.

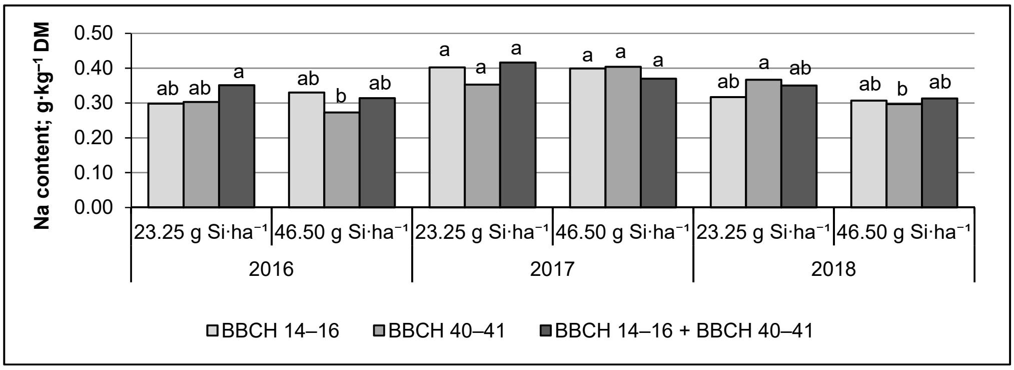

Figure 1. Sodium (Na) content in potato tuber in relation to year, dosage and time of silicon application. Time of silicon application: the leaf development stage, BBCH 14–16; tuber initiation stage, BBCH 40–41; both leaf development stage and tuber initiation stage, BBCH 14–16 + BBCH 40–41. Means for each year followed by the same letters do not differ significantly at $p \leq 0.05$.

The macronutrient content in early crop potato tubers depended to a greater extent on the weather conditions during potato growth than on the silicon application. Regardless of treatment (with or without Si), most of the K, Ca and Na and, at the same time, the least of the P were accumulated by potato tubers in the warm and moderately wet growing season of 2017. The highest concentrations of Mg were accumulated by potato tubers in 2016, with periodic water deficits, but with the highest content of available Mg in soil (Table 3).

3.2. Macronutrient Ionic Ratios

Silicon had a significant effect on the mass ratios of Na^+/Ca^{2+} and Na^+/Mg^{2+} in potato tubers but had no effect on the mass ratios of K^+/Ca^{2+}, K^+/Mg^{2+}, $(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$ or Ca/P (Table 5). Following silicon application, the mass ratios of Na^+/Ca^{2+} and Na^+/Mg^{2+} in tubers were narrower compared with the untreated control tubers, especially under water-deficit conditions during potato growth in 2016 and 2018.

Table 5. Effect of silicon (Si) on macronutrient ionic ratios in potato tubers.

Treatment	Year			Mean
	2016	2017	2018	
		K^+/Ca^{2+}		
Control	76.04 a	68.70 a	87.44 a	77.39 a
With Si	81.72 a	78.34 a	86.21 a	82.11 a
		K^+/Mg^{2+}		
Control	22.11 a	28.72 a	25.54 a	25.46 a
With Si	21.91 a	29.50 a	27.12 a	26.18 a
		Na^+/Ca^{2+}		
Control	1.558 a	1.452 a	1.762 a	1.590 a
With Si	1.296 b	1.494 a	1.471 b	1.420 b
		Na^+/Mg^{2+}		
Control	0.453 a	0.585 a	0.531 a	0.523 a
With Si	0.349 b	0.580 a	0.461 b	0.454 b
		$(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$		
Control	17.40 a	20.64 a	20.01 a	19.35 a
With Si	17.43 a	22.36 a	20.94 a	20.28 a
		Ca/P		
Control	0.117 a	0.167 a	0.100 a	0.128 a
With Si	0.114 a	0.148 a	0.101 a	0.121 a

Means within columns for each data type followed by the same letters do not differ significantly at $p \leq 0.05$.

4. Discussion

In sustainable plant production focusing on high value products, trace elements have been gaining increasing importance. The use of some beneficial elements can enhance plant nutrient uptake and assimilation [7,8]. The exogenous application of silicon enhanced mineral accumulation by some grain [10] and fruit [20,21] crops under salt or drought stresses, whereas little is known of the effect of silicon on mineral accumulation by root [19] and tuber plants [23,24]. Although potato is a silicon low-accumulator, foliar silicon application may contribute to enhancing tuber yield and quality when properly employed [26].

Foliar silicon (Na_2SiO_3) application in the commercial product Optysil increased early potato yield under water deficit on Haplic Luvisol soil [27] but did not affect the macronutrient contents in tubers, except for Na. In the present study, the silicon reduced Na accumulation by potato tubers, especially under water deficit during tuber bulking. As a result, the mass ratios of Na^+/Ca^{2+} and Na^+/Mg^{2+} in these tubers were narrower than in the untreated control tubers. Sodium (Na) is not a plant nutrient, but it is an important mineral for humans. Potato plants uptake nutrients primarily from the soil solution through their roots. Most macronutrients are taken up by a combination of two mechanisms, active and passive [28]. The takeup of Na is essentially a passive process [29]. The behavior of the Na showed a negative correlation with some elements [30]. Several studies showed the ability of silicon to reduce Na uptake by plants. The possible mechanisms of Si-induced reduction in the Na uptake by plants include regulating the expression of ion transporter genes, stimulating H-ATPase activity and plasma membrane selectivity, or a mechanical barrier for root-to-shoot translocation of Na via the apoplastic bypass route [16,31]. Discussion of the study results with data presented by other researchers is difficult because previous studies were carried out under greenhouse conditions [22] or as a one-year field experiment [23,24]. Mineral accumulation by potato tubers is affected by growth conditions [4,6]. Soltani et al. [22] reported that silicon application at the nano- and micro-scale (nano-silica, sodium silicate, nano-clay, and Bentonite) increased K and P accumulation and reduced Mg accumulation by mini-tubers of late potato cultivar Agria under greenhouse conditions, which was not confirmed in the present study with the foliar application of sodium metasilicate under uncontrolled field conditions. Silicon's effect on the growth and nutrient uptake of potato mini-tubers depended on its source. Silicon in nano-fertilizers was more effective [22]. Nano-fertilizers, based on nanoparticles, improve nutrient release kinetics and plant uptake efficiency [13,14]. The foliar-applied silicon in the form of sodium metasilicate is accumulated mainly in the leaves [14]. A one-year field experiment in Iran showed that foliar application of silicon (silica (SiO_2) or sodium silicate nanoparticles (Nano-$NaSiO_3$) increased the K content in the leaves of late potato cultivar Agria under salinity stress on silty loam soil and reduced the Na^+/K^+ ratio [23]. In the present study, foliar silicon (Na_2SiO_3) application did not affect the K accumulation by tubers of very-early potato cultivar Catania on Haplic Luvisol with a sandy loam texture. Salinity stress increased Na and reduced K concentration in potato leaves. The application of Nano-$NaSiO_3$ increased the osmotic potential of the leaf, preventing the entry and accumulation of Na ions. As result, the application of silicon reduced Na and increased K accumulation under saline conditions [23]. Previously, a one-year field experiment in Poland did not show an effect of foliar application of orthosilicic acid (H_4SiO_4) in the commercial product Actisil on the K, P, Ca or Mg accumulation by tubers of medium-late cultivar Yelly on a medium-compact soil [24]. This was confirmed in the present study by applying sodium metasilicate in the commercial product Optysil in the cultivation of the very-early potato cultivar Catania. In agriculture, the most common form of silicon used is orthosilicic acid or silicate salts (calcium silicate, potassium silicate or sodium silicate) [10]. Silicon taken up by a plant is deposited in the form of SiO_2 on the leaf apoplast [32]. The genotypic variability and environmental conditions play a dominant role in the variability of macronutrient content and their ionic ratios in potato tubers [4,33,34].

Foliar application of silicon is practical only at a very low dosage and starting early in the vegetative stage [35,36]. There is scarce knowledge of the effect of different dosages and time of foliar silicon application on the nutrient content in potato tubers. In the present study, the effect of dosage and time of silicon application on the Na content in early crop potato tubers depended on a water deficit during potato growth. Silicon dosage (23.25 g Si·ha^{-1} or 46.50 g Si·ha^{-1}) significantly affected the Na accumulation by potato tubers only in the warm and very dry growing season of 2018. Under drought stress, silicon at 46.50 g Si·ha^{-1} (0.50 dm^3·ha^{-1} of Optysil) reduced the Na content in potato tubers more than at 23.25 g Si·ha^{-1} (0.25 dm^3·ha^{-1} of Optysil). Under periodic water deficits, the time of silicon application affected the Na accumulation by potato tubers more than the silicon dosage. The Na content in tubers was the highest with two silicon applications, first in the leaf development stage, and with repeated treatment in the tuber initiation stage.

Potatoes are an important source of minerals in the human diet. The nutritional value of potatoes is determined not only by the general content of individual macronutrients but also by their ionic ratios. Although silicon reduced Na accumulation, the ratio of the sum of univalent cations to the sum of bivalent cations $(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$ in tubers was at the same level, both in cultivations with and without silicon.

5. Conclusions

Foliar silicon (Na_2SiO_3) application in the commercial product Optysil had no effect on the K, P, Ca, or Mg content in early crop (75 days after planting) potato tubers but reduced Na accumulation, especially under water deficit conditions during tuber bulking. Silicon dosage significantly affected the Na accumulation by potato tubers only in the warm and very dry growing season. Under drought stress, silicon at 46.50 g $Si \cdot ha^{-1}$ (0.50 $dm^3 \cdot ha^{-1}$ of Optysil) reduced the Na content in potato tubers more than at 23.25 g $Si \cdot ha^{-1}$ (0.25 $dm^3 \cdot ha^{-1}$ of Optysil). Under periodic water deficits, the time of silicon application affected the Na accumulation by potato tubers more than the silicon dosage. The Na content in tubers was the highest with two silicon applications, first in the leaf development stage (BBCH 14–16), and with repeated treatment in the tuber initiation stage (BBCH 40–41). Although Optysil reduced the Na accumulation and mass ratios of Na^+/Ca^{2+} and Na^+/Mg^{2+}, the ratio of the sum of univalent cations to the sum of bivalent cations $(K^+ + Na^+)/(Ca^{2+} + Mg^{2+})$ in tubers was at the same level, both in cultivations with and without silicon. These results increased the current knowledge on the effect of foliar silicon application on macronutrient accumulation by potato tubers. However, future studies are necessary to evaluate the responses of different potato cultivars to silicon and determine the effect of different silicon sources and concentrations.

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