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Potato (*Solanum tuberosum* L.) Growth in Response to Foliar Silicon Application

Wanda Wadas

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

Abstract: As silicon induces abiotic stress tolerance in crop plants, it was hypothesized that foliar silicon application could improve potato growth in an early crop culture. The effect of dosage (0.25 $dm^3 \cdot ha^{-1}$ or 0.50 $dm^3 \cdot ha^{-1}$) and time (the leaf development stage, BBCH 14–16, tuber initiation stage, BBCH 40–41, or both the leaf development stage and tuber initiation stage) of application of the silicon-based biostimulant Optysil (200 g SiO_2 and 24 g Fe in 1 dm^3) on potato growth was investigated. Optysil caused an increase in plant height and above-ground plant biomass, enlarged leaf area and decreased leaf weight ratio (LWR), and, as a result, increased tuber number and tuber weight per plant. The effect of Optysil depended on a water deficit during potato growth. The average tuber weight per plant in the cultivation treated with Optysil was higher by 23% under periodic water deficits during potato growth, and by 13% under drought conditions, than in the cultivation without the biostimulant. Dosage of Optysil had a significant effect on above-ground plant biomass and leaf area in the warm and arid growing season. Under drought stress, Optysil at 0.50 $dm^3 \cdot ha^{-1}$ stimulated potato growth more than at 0.25 $dm^3 \cdot ha^{-1}$. Under periodic water deficits during potato growth, the time of Optysil application affected potato growth more than the biostimulant dosage. The plants produced greater above-ground biomass and had a larger leaf area with two Optysil applications; one in the initial plant growth period (BBCH 14–16), and a repeated treatment in the tuber initiation stage (BBCH 40–41). The tuber weight per plant was positively correlated with the plant height, above-ground plant biomass, leaf area, and LWR.

Keywords: sodium silicate; biostimulant; plant height; above-ground biomass; leaf area; tuber weight

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1. Introduction

Although silicon is not considered an essential element for plants, it plays an essential role in plant growth by regulating physiological and biochemical processes [1,2]. Silicon can influence plant–water relations, improve the process of photosynthesis and nutrient uptake, regulate phytohormone biosynthesis and the activities of certain enzymes, and decrease oxidative stress [3,4]. The beneficial effects of silicon are particularly distinct under environmental-stress conditions [3,5,6]. Since silicon plays an essential role in mitigating biotic and abiotic stresses (high temperature, freezing, drought, salt stress, disease and insect stress, and other stress factors) on plants [4,5,7–10], the use of silicon as a biostimulant to improve plant growth under stress conditions and increase crop productivity has been increasing.

Silicon can be applied as a biostimulant through foliar spraying, incorporation into the soil, or fertigation. Foliar application of silicon is more effective than soil application [11]. The beneficial effects of foliar silicon application on plant growth under stress conditions have been reported on for several agricultural and horticultural plants, including rice [12], wheat [13], canola [14], sugar beet [15], tomato [16], cucumber [17], and onion [18]. To date, few studies have focused on the effect of silicon on potato growth. Nearly all experiments were carried out in a hydroponic culture or pots in a greenhouse [19–25]. There is insufficient knowledge of the effect of silicon on potato growth under uncontrolled environmental conditions in the field.

Silicon ($NaSiO_3$) added to a nutrient solution at low concentration (0.5 mM Si) induced enlargement of the leaf area, and increased the leaf numbers and leaf and stem biomass of potato plants grown in a hydroponic system. Higher silicon concentrations in the nutrient solution reduced the values of potato growth parameters, mainly in leaf area. There was a genotypic variation in the potato-plant response to silicon [19]. A greenhouse pot experiment showed that soil silicon (Ca and Mg silicate) application increased plant height and reduced stem lodging, and increased tuber weight per plant and mean tuber weight, especially in the absence of water stress [20,21]. Another greenhouse pot experiment showed that both soil (SiO_2 in the commercial product FertiSilica) and foliar (orthosilicic acid (H_4SiO_4) and disilicic acid (H_2SiO_5) in the commercial product Silamol) silicon application increased stem length, number of leaves, leaf area, specific leaf area (SLA), and leaf area ratio (LAR). Only soil silicon application increased dry weight of leaves and stems [22,23]. A study carried out in vitro and under greenhouse conditions showed that foliar silicon (silicon dioxide nanoparticles; SiO_2-NPs) application at a low dosage (50 mg dm^{-1}) improved potato growth under salinity stress [24]. According to other authors, silicon in nano-silica, nano clay, or Bentonite increased potato stem diameter and leaf dry weight under greenhouse conditions. In contrast, sodium silicate did not affect those potato growth traits. Sodium silicate had a greater effect on root growth [25]. A one-year field experiment in Iran showed that foliar application of silicon (silica (SiO_2) or sodium silicate nanoparticles (Nano-$NaSiO_3$)) increased tuber number per plant and tuber yield of late potato cultivar Agria under salinity stress [26]. Foliar application of silicon is practical only at very low dosages, and starting early in the vegetative stage [19,24,27].

The current study aimed to determine the effect of foliar silicon application on potato growth under uncontrolled environmental conditions in the field. In the current study, obtained results suggested that foliar silicon application could improve potato growth under abiotic stress conditions, such as periodic water deficits or drought. Likewise, the assumption that potato response to foliar silicon application depends on the dosage and time of application.

2. Materials and Methods

2.1. Experimental Site and Season

The field experiment was carried out in central-eastern Poland (52°03′ N, 22°33′ E) over three growing seasons (2016–2018), using Haplic Luvisol, with a sandy loam texture. The soil was characterized by an acidic–slightly-acidic reaction, high content of available P, medium–high content of K, and low–medium content of Mg (Table 1).

Table 1. Soil chemical properties at the experimental site.

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

In each year of the study, spring triticale was grown as a potato forecrop. 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. Colorado potato beetle (*Leptinotarsa decemlineata*) was controlled using thiamethoxam (Actara 25 WG; Syngenta Crop Protection AG, Basel, Switzerland).

The weather conditions during the potato growth periods were different (Table 2). Hydrothermal conditions during potato growth were characterized by Sielianinov's hydrothermal index (k), calculated following the formula: $k = 10\ P/\Sigma t$, where P: the sum of the monthly rainfalls in mm, and Σt: the monthly total air temperature > 0 °C) [28]. The year 2016 was warm, with periodic water deficits, during potato growth. The following year (2017) was warm and moderately wet, whereas 2018 was warm and very dry.

Table 2. Hydrothermal conditions during potato growing period.

Month	Temperature; °C			Rainfall; mm			Hydrothermal Index		
	2016	2017	2018	2016	2017	2018	2016	2017	2018
April	9.1	6.9	13.1	28.7	59.6	34.5	1.05	2.88	0.88
May	15.1	13.9	17.0	54.8	49.5	27.3	1.17	1.15	0.52
June	18.4	17.8	18.3	36.9	57.9	31.5	0.67	1.08	0.57

Hydrothermal index: up to 0.4, extremely dry; 0.41–0.7, very dry; 0.71–1.0, dry; 1.01–1.3, rather dry; 1.31–1.6, optimal; 1.61–2, rather humid; 2.01–2.5, humid; 2.51–3, very humid; >3, extremely humid [28].

2.2. Experimental Design

In this experiment, the silicon (Si) source was the biostimulant Optysil, produced by Intermag Ltd., Olkusz, Poland. Optysil contains 200 g SiO_2 (16.5 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 effect of dosage and time of Optysil application on potato growth was determined.

The field experiment was established as a split-plot design with a control object without the biostimulant, with three replications. The experimental factors were: Factor A, Optysil dosage: 0.25 $dm^3 \cdot ha^{-1}$ or 0.50 $dm^3 \cdot ha^{-1}$; and Factor B, time of Optysil application: in leaf development stage (under the terms of uniform codes of phenologically similar growth stages of plant species, by Biologische Bundesanstalt, Bundessortenamt and Chemical Industry; 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) [Meier 2018]. Potato plants sprayed with water were used as a control. A single plot control was located between the main plots.

The very early potato-cultivar Catania (Europlant Pflanzenzucht GmbH, Lüneburg, Germany) was grown. Six-week pre-sprouted seed potatoes were planted on 6 April 2016, 10 April 2017, and 9 April 2018, with an in-row spacing of 25 cm, and 67.5 cm between rows. The average length of sprouts at the time of planting was 15–20 mm. The plots were six rows wide and 4 m long (96 plants per plot).

In the tuber formation stage (BBCH 46–48), the height of plants, fresh and dry weight of stems and leaves, leaf area, leaf weight ratio (LWR), and leaf area ratio (LAR) were determined. The measurements were made on four successive randomized plants per plot. Leaf area was measured by the weight method, based on the weight of pieces with a known diameter and the total weight of leaves per plant [29]. LWR and LAR were defined as the ratio of weight of leaves/weight of the whole plant, and leaf area/weight of the whole plant, respectively [30]. Potatoes were harvested 75 days after planting (the end of June). Tuber number and tuber weight per plant were determined on ten successive randomized plants per plot. The relationship between tuber weight and potato-plant growth traits was also determined.

2.3. Statistical Analysis

The study results were analyzed statistically using an analysis of variance (ANOVA) for the split-plot design (Optysil dosage × time of Optysil application × year), with a control object. The analysis of the results was conducted using the orthogonal contrast to compare the control, without Optysil, with the test objects, with Optysil. The significance of sources of variability was tested using the *F* Fisher–Snedecor test and the differences between the compared averages was verified using Tukey's test ($p \leq 0.05$). Linear correlation was used to determine the relationship between tuber weight and potato-plant growth traits ($n = 21$).

3. Results

3.1. Plant Height and Above-Ground Plant Biomass

The silicon-based biostimulant Optysil had a significant effect on potato growth. The plants were taller and produced greater above-ground biomass (Table 3). The effect of Optysil depended on the hydrothermal conditions during potato growth. Optysil significantly affected plants' height and above-ground plant biomass in water-deficit conditions in 2016 and 2018. In the warm growing season in 2016, with periodic water deficits during potato growth, the treated plants were taller by 3.0 cm, on average, average stem fresh weight was higher by 22.7 g (16%), and average leaf fresh weight was higher by 10.3 g (6%) compared with the control plants. The differences in the average dry weight of stems and leaves were 2.3 g (17%) and 4.8 g (23%), respectively. In the warmer and very dry growing season of 2018, following the application of Optysil, the plants were taller by an average of 2.4 cm, fresh stem weight was higher by 24.2 g (25%), and fresh leaf weight was higher by 15.6 g (14%) compared with the control plants. Average dry weight of stems and leaves for treated plants was higher by 2.2 g (20%) and 1.8 g (11%), respectively.

Table 3. Effect of Optysil on plant height and above-ground plant biomass.

Treatment	Year			Mean
	2016	2017	2018	
Plant height; cm				
Control	31.2 ± 1.2 [b]	51.1 ± 1.9 [a]	31.9 ± 0.9 [b]	38.1 ± 9.8 [b]
With Optysil	34.2 ± 1.7 [a]	49.6 ± 2.7 [a]	34.3 ± 1.1 [a]	39.4 ± 7.6 [a]
Fresh stem weight; g				
Control	140.8 ± 11.2 [b]	259.3 ± 7.2 [a]	96.7 ± 4.7 [b]	166.3 ± 72.5 [b]
With Optysil	163.5 ± 23.6 [a]	249.0 ± 34.9 [a]	120.9 ± 14.2 [a]	177.8 ± 59.3 [a]
Dry stem weight; g				
Control	11.2 ± 0.4 [b]	16.8 ± 1.8 [a]	10.8 ± 0.8 [b]	12.9 ± 3.1 [b]
With Optysil	13.5 ± 2.2 [a]	16.6 ± 2.3 [a]	13.0 ± 1.6 [a]	14.0 ± 2.3 [a]
Fresh leaf weight; g				
Control	169.2 ± 4.2 [b]	213.8 ± 6.3 [a]	110.2 ± 1.3 [b]	164.4 ± 45.2 [b]
With Optysil	179.5 ± 26.3 [a]	209.2 ± 23.1 [a]	125.8 ± 12.3 [a]	171.5 ± 40.7 [a]
Dry leaf weight; g				
Control	21.0 ± 2.5 [b]	22.9 ± 3.0 [a]	16.6 ± 1.5 [b]	20.2 ± 3.2 [b]
With Optysil	25.8 ± 3.1 [a]	23.4 ± 3.3 [a]	18.4 ± 2.0 [a]	22.5 ± 4.2 [a]

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

The dosage and time of Optysil application did not affect plant height. The study demonstrated a significant interaction effect between year and dosage of Optysil on the weight of stems and leaves, and an interaction between year and time of Optysil application on stem weight. Optysil dosage significantly affected the weight of stems and leaves, only in the warm and arid growing season of 2018 (Table 4). After applying 0.50 $dm^3 \cdot ha^{-1}$ of Optysil, fresh stem weight was higher, on average, by 21.6 g (20%), and fresh leaf weight was higher by 18.2 g (16%) compared to the values of the 0.25 $dm^3 \cdot ha^{-1}$ dosage. The differences in dry-stem and -leaf weights were 1.6 g (13%) and 1.9 g (11%), respectively. The time of Optysil application had a significant effect on stem weight in 2016, with periodic water deficits during potato growth. In that year, fresh- and dry-stem weights were the highest with two Optysil applications, first in the leaf development stage, with repeated treatment in the tuber formation stage (BBCH 14–16 and BBCH 40–41).

Table 4. Effect of Optysil dosage on plant height and above-ground plant biomass.

Optysil Dosage	Year			Mean
	2016	2017	2018	
Plant height; cm				
0.25 $dm^3 \cdot ha^{-1}$	33.8 ± 1.4 [a]	49.7 ± 2.9 [a]	34.2 ± 0.9 [a]	39.3 ± 7.8 [a]
0.50 $dm^3 \cdot ha^{-1}$	34.5 ± 2.0 [a]	49.5 ± 2.7 [a]	34.4 ±1.2 [a]	39.5 ± 7.5 [a]
Fresh stem weight; g				
0.25 $dm^3 \cdot ha^{-1}$	161.7 ± 27.2 [a]	257.3 ± 34.3 [a]	110.1 ± 10.3 [b]	176.4 ± 66.9 [a]
0.50 $dm^3 \cdot ha^{-1}$	165.3 ± 20.8 [a]	240.6 ± 35.4 [a]	131.7 ± 7.7 [a]	179.2 ± 51.9 [a]
Dry stem weight; g				
0.25 $dm^3 \cdot ha^{-1}$	13.2 ± 2.0 [a]	15.9 ± 2.3 [a]	12.2 ± 1.7 [b]	13.8 ± 2.4 [a]
0.50 $dm^3 \cdot ha^{-1}$	13.7 ± 2.5 [a]	15.2 ± 2.4 [a]	13.8 ± 1.9 [a]	14.2 ± 2.3 [a]
Fresh leaf weight; g				
0.25 $dm^3 \cdot ha^{-1}$	181.5 ± 4.3 [a]	216.4 ± 6.3 [a]	116.7 ± 1.3 [b]	171.5 ± 46.4 [a]
0.50 $dm^3 \cdot ha^{-1}$	177.4 ± 26.3 [a]	202.0 ± 23.1 [a]	134.9 ± 12.3 [a]	171.4 ± 35.0 [a]
Dry leaf weight; g				
0.25 $dm^3 \cdot ha^{-1}$	25.3 ± 3.4 [a]	23.1 ± 3.5 [a]	17.5 ± 1.7 [b]	22.0 ± 4.4 [a]
0.50 $dm^3 \cdot ha^{-1}$	26.2 ± 2.9 [a]	23.6 ± 3.2 [a]	19.4 ± 2.0 [a]	23.1 ± 3.9 [a]

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

The effect of the interaction of year and dosage and time of Optysil application on the weight of stem and leaves was not statistically confirmed.

3.2. Leaf Area, Leaf Weight Ratio (LWR) and Leaf Area Ratio (LAR)

Optysil caused enlargement of leaf area, and decreased leaf area ratio (LAR), but did not affect leaf weight ratio (LWR) (Table 5). The effect of Optysil depended on the hydrothermal conditions during potato growth. Foliar silicon application significantly affected leaf area and LAR under water deficit in 2016 and 2018. In the warm growing season of 2016, with periodic water deficits during potato growth, Optysil caused enlargement of leaf area by an average of 578 cm^2 (14%), and decreased LAR by 8.6 $cm^2 \cdot g^{-1}$ compared with the control plants. In the warmer and very dry growing season of 2018, following the application of Optysil, leaf area was larger by an average of 327 cm^2 (9%), and the LAR value was lower by 6.7 $cm^2 \cdot g^{-1}$ compared with the control plants.

Table 5. Effect of Optysil on leaf area, leaf weight ratio (LWR) and leaf area ratio (LAR).

Treatment	Year			Mean
	2016	2017	2018	
Leaf area; cm^2				
Control	4240 ± 305 [b]	6006 ± 102 [a]	3571 ± 210 [b]	4605 ± 1091 [b]
With Optysil	4818 ± 568 [a]	5784 ± 894 [a]	3898 ± 380 [a]	4833 ± 1005 [a]
Leaf weight ratio (LWR); $g \cdot g^{-1}$				
Control	0.653 ± 0.013 [a]	0,579 ± 0.015 [a]	0.606 ± 0.014 [a]	0.613 ± 0.033 [a]
With Optysil	0.659 ± 0.026 [a]	0.602 ± 0.035 [a]	0.589 ± 0.032 [a]	0.617 ± 0.043 [a]
Leaf area ratio (LAR); $cm^2 \cdot g^{-1}$				
Control	132.0 ± 3.6 [a]	153.5 ± 4.9 [a]	131.3 ± 8.4 [a]	138.9 [a]
With Optysil	123.4 ± 8.4 [b]	147.9 ± 10.8 [a]	124.6 ± 8.7 [b]	132.0 [b]

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

The dosage and time of Optysil application had a significant effect on leaf area but, did not affect LAR. This study demonstrated the significant effect of the interaction of year and dosage of Optysil, and the interaction of year and time of Optysil application on leaf area. The Optysil dosage significantly affected leaf area only in the warm and very dry growing season of 2018. In that year, after applying 0.50 $dm^3 \cdot ha^{-1}$ of Optysil, leaf area was larger by an average of 534 cm^2 (12%) compared with the values of the 0.25 $dm^3 \cdot ha^{-1}$ dosage. The time of Optysil application had a significant effect on leaf area in 2016 with periodic water deficits during potato growth (Table 6). In that year, leaf area was the largest with two Optysil applications, first in the leaf development stage, with a repeated treatment in the tuber formation stage (BBCH 14–16 and BBCH 40–41).

Table 6. Effect of time of Optysil application on leaf area and leaf area ratio (LAR).

Time of Optysil Application	Year			Mean
	2016	2017	2018	
Leaf area; cm^2				
BBCH 14–16	4776 ± 494 [b]	5825 ± 833 [a]	4103 ± 436 [a]	4901 ± 929 [a,b]
BBCH 40–41	4325 ± 393 [b]	5764 ± 414 [a]	3801 ± 181 [a]	4630 ± 914 [b]
BBCH 14–16 and BBCH 40–41	5352 ± 250 [a]	5763 ± 679 [a]	3791 ± 439 [a]	4969 ± 1176 [a]
Leaf area ratio (LAR); $cm^2 \cdot g^{-1}$				
BBCH 14–16	129.9 ± 8.6 [a]	147.8 ± 12.6 [a]	128.4 ± 8.8 [a]	135.4 ± 13.2 [a]
BBCH 40–41	118.6 ± 8.3 [a]	150.4 ± 10.7 [a]	121.7 ± 6.0 [a]	130.2 ± 45.2 [a]
BBCH 14–16 and BBCH 40–41	121.8 ± 3.7 [a]	145.5 ± 10.5 [a]	123.8 ± 10.7 [a]	130.4 ± 13.9 [a]

Time of Optysil 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 $p \leq 0.05$.

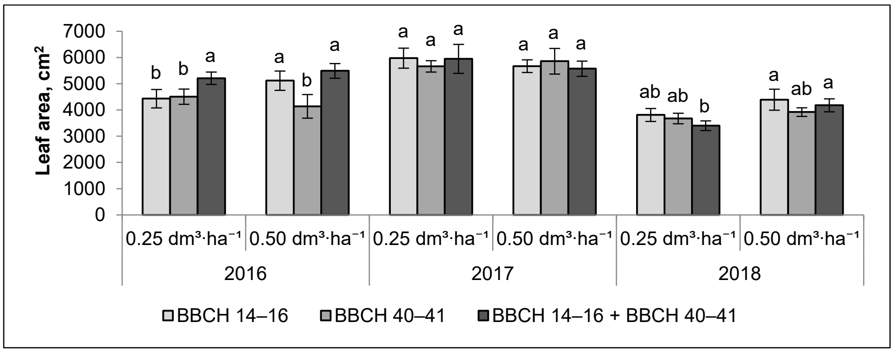
The study demonstrated the significant effect of the interaction of year, dosage and time of Optysil application on leaf area and LAR. In 2016, with drought periods during potato growth, the plants produced the largest leaf area with two Optysil applications at 0.50 $dm^3 \cdot ha^{-1}$, first in the leaf development stage, with a repeated treatment in the tuber initiation stage (BBCH 14–16 and BBCH 40–41). In the very dry growing season of 2018, the leaf area was largest after applying 0.50 $dm^3 \cdot ha^{-1}$ of Optysil in the leaf development stage (BBCH 14–16) (Figure 1). As a result, the LAR values of these plants were lower than those of the other treated plants.

3.3. Tuber Number and Tuber Weight

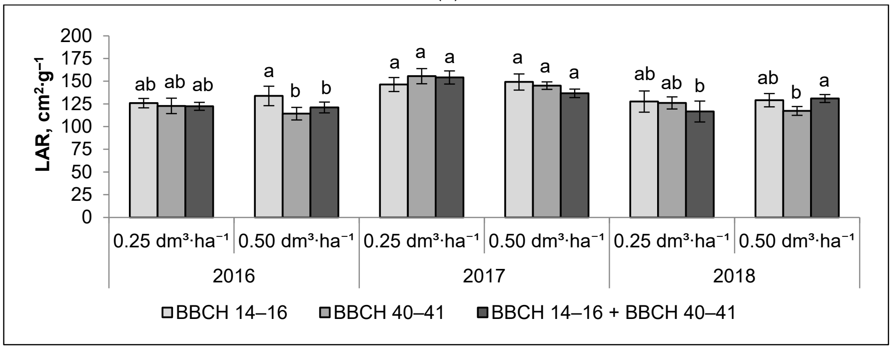
Optysil caused an increase in tuber number and tuber weight per plant. The yield-increasing effect of the biostimulant depended on hydrothermal conditions during potato growth (Table 7). Optysil caused the highest increase in tuber number and tuber weight per plant in 2016, with drought periods during potato growth. In that year, the average tuber number for the treated plants was higher by 2.7, and tuber weight by 83.3 g (23%), compared with the control plants. In the very dry growing season of 2018, following the application of Optysil, tuber number per plant was higher by an average of 1.1, and tuber weight was higher by 22.3 g (13%), compared with the control plants.

The dosage and time of Optysil application had no significant effect on tuber number or tuber weight per plant. The interaction of year, dosage, and time of Optysil application on tuber number and tuber weight per plant was not statistically confirmed.

Tuber weight per plant was strongly positively correlated with leaf weight, leaf area, LWR, and tuber number. A significant positive correlation was also found between tuber weight, plant height, and stem fresh weight (Table 8).



(**a**)



(**b**)

Figure 1. Leaf area (**a**) and leaf area ratio (LAR) (**b**) in relation to year, dosage and time of Optysil application. Time of Optysil 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 followed by the same letters do not differ significantly at $p \leq 0.05$.

Table 7. Effect of Optysil on tuber number and tuber weight.

Treatment	Year			Mean
	2016	**2017**	**2018**	
	Tuber number			
Control	15.2 ± 0.8^{b}	10.6 ± 0.9^{a}	6.4 ± 0.7^{b}	10.7 ± 3.9^{b}
With Optysil	17.9 ± 1.8^{a}	10.9 ± 0.7^{a}	7.5 ± 0.8^{a}	12.1 ± 4.6^{a}
	Tuber weight; g			
Control	361.3 ± 17.5^{b}	407.3 ± 14.1^{a}	170.7 ± 13.2^{b}	313.1 ± 109.1^{b}
With Optysil	444.6 ± 39.2^{a}	424.4 ± 30.0^{a}	193.0 ± 29.4^{a}	354.0 ± 119.7^{a}

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

Table 8. Linear correlation coefficients (n = 21) between tuber weight per plant and plant growth characteristics.

Plant Growth Traits	Correlation Coefficient
Plant height	0.46 *
Fresh stem weight	0.66 **
Dry stem weight	0.39
Fresh leaf weight	0.82 **
Dry leaf weight	0.80 **
Leaf area	0.67 **
Leaf weight ratio (LWR)	0.56 **
Leaf area ratio (LAR)	0.35
Tuber number	0.77 **

*–significant at $p \leq 0.05$; **–significant at $p \leq 0.01$.

4. Discussion

In sustainable agriculture, the application of silicon has been increasing as an environmentally friendly technique to stimulate plant growth and alleviate biotic and abiotic stresses [6,8,9,31]. Plant growth is important in the analysis of the silicon effect on crop yielding. Previously, greenhouse pot experiments showed that silicon applied via soil or leaves stimulated potato growth [20–23,26], which was confirmed in the present study under uncontrolled environmental conditions in a field. The silicon-based (Na_2SiO_3) biostimulant Optysil improved the growth of the drought-sensitive very-early potato-cultivar Catania under water deficit. The plants treated with Optysil were taller, had a larger leaf area, and produced greater above-ground biomass than those in the cultivation without the biostimulant. The effect of Optysil depended on a water deficit during potato growth. Silicon induces drought tolerance in crop plants by regulating physiological and biochemical processes, including water relations, photosynthesis, nutrient uptake, reduction in oxidative stress, osmotic adjustment, and expression of genes associated with the mitigation of drought stress phytohormone synthesis [2–4,32]. A greenhouse pot experiment showed that foliar silicon application maintained relative water content, increased proline and the activity of antioxidant enzymes, such as catalase (CAT) and superoxide dismutase (SOD), and decreased hydrogen peroxide (H_2O_2) concentration in potato plants under water deficit [23].

In the present study, Optysil caused an enlargement of leaf area and increased leaf and stem fresh and dry weight. As a result, leaf area ratio (LAR), which describes the weight per unit of leaf area, of treated plants was lower in the treated cultivation than in the cultivation without the biostimulant. Optysil did not affect on leaf weight ratio (LWR), which describes the amount of assimilation organs in the whole plant. In a study carried out by other authors, foliar silicon (orthosilicic acid, H_4SiO_4, and disilicic acid, H_2SiO_5, in the commercial product Silamol) application increased leaf area and LAR of very-early cultivar Agata (resistant to a short-term drought), under greenhouse conditions [22]. LAR and LWR are determined by potato cultivar, plant growth stage, and the interaction between the cultivar and the environment. These indices varied with plant growth due to potato response to weather conditions, changes caused by fall, or new growth of leaves. LAR decreases almost linearly with the growth of plants. During ontogenesis, LWR decreases faster than LAR [30,33–35]. Soltani et al. [25] reported that the silicon effect on potato growth depended on its source. A genotypic variation in the potato response to silicon was also observed [19].

Environmental factors, agricultural practice, and treatment timing can influence the effectiveness of plant biostimulants [36]. Silicon exhibits the properties of a biostimulant only at low dosages, and when its application starts early in the vegetative stage [19,24,27]. Higher concentrations of silicon (2.5 mM as $NaSiO_3$) in a nutrient solution induced a reduction im potato growth parameters (leaf area, leaf number, leaf, and stem biomass), mainly in leaf area. The concentration of 0.5 mM Si was optimal for improving potato growth [19]. Foliar silicon (silicon dioxide nanoparticles SiO_2-NPs) application, at a low dosage (50 $mg{\cdot}dm^{-3}$), improved potato growth under salinity stress, whereas at a higher dosage (100 $mg{\cdot}dm^{-3}$) it reduced all plant-growth trait values [24]. In the present study, potato growth in response to the dosage and time of Optysil application depended on a water deficit during plant growth. Optysil dosage (0.25 $dm^3{\cdot}ha^{-1}$ or 0.50 $dm^3{\cdot}ha^{-1}$) significantly affected leaf and stem fresh and dry weights, and leaf area, only in the warm and very dry growing season of 2018. Under drought stress, Optysil at 0.50 $dm^3{\cdot}ha^{-1}$ stimulated the growth of above-ground plant parts more than at 0.25 $dm^3{\cdot}ha^{-1}$, but the dosage of Optysil had no effect on the weight per unit of leaf area (LAR). Under periodic water deficits, the time of Optysil application affected potato growth more than the biostimulant dosage. The time of Optysil application did not affect leaf weight. The plants produced greater biomass of stems, and had a larger leaf area, with two Optysil applications, first in the initial plant growth period (BBCH 14–16), with a repeated treatment in the tuber initiation stage (BBCH 40–41). Under drought stress, leaf area was largest, and

LAR as lower, when Optysil was applied at 0.50 $dm^3 \cdot ha^{-1}$ only in the initial potato growth period (BBCH 14–16). It would suggest that, under periodic water deficits, potato growth is stimulated more by applying a lower dose of silicon several times, whereas, under drought conditions, is more effective to apply a higher dose of silicon in the initial potato growth stage. In the present study, the growing period of potatoes was short; only 75 days from planting to harvest. In such a short period, the effect of dosage and time of foliar silicon application on potato growth and productivity may be smaller or unnoticed.

The plants treated with Optysil produced greater above-ground biomass and had a larger leaf area than those in the cultivation without the biostimulant. The enlargement of leaf area does not always increase tuber weight, because the rate of photosynthesis per unit of leaf area decreases with an increase in leaf area [30]. In addition, potato plants respond very sensitively to weather changes during vegetation, which may cause the fall or growth of new leaves. Leaf area index (LAI) describes the growth in lowland fields, and increases progressively over time, reaching its maximum at 60 days after potato planting and declining after that time point [37,38]. In the present study, the silicon-based (Na_2SiO_3) biostimulant Optysil caused an increase in tuber number and tuber weight per plant under water deficit in 2016 and 2018 seasons. Following the application of Optysil, the average tuber weight per plant was higher by 23% under periodic water deficits during potato growth (2016 season), and by 13% under drought conditions (2018 season), than in the cultivation without the biostimulant. A water shortage during the tuber bulking period decreases yields more significantly than drought during other growth stages [39]; this was confirmed in the present study. The dosage and time of Optysil application slightly affected tuber number and tuber weight per plant. Previously, a one-year field experiment in Iran showed that a two-time (40 and 50 days after potato planting) foliar application of silica SiO_2 (1000 ppm), or sodium silicate nanoparticles Nano-$NaSiO_3$ (400 ppm), increased tuber number per plant and tuber yield of the late potato cultivar, Agria, under salinity stress. The silicon in sodium silicate nanoparticles was more effective [26]. Tuber weight per plant was positively correlated with plant height, above-ground plant biomass, leaf area and LWR, and tuber number. A positive correlation between leaf area and tuber yield suggested that the enlargement of leaf area could enhance the export of photosynthetic products and cause an increase in tuber weight [40].

5. Conclusions

Foliar silicon application can effectively improve plant growth and increase early crop potato yield under a water deficit. Under drought stress, the silicon-based (Na_2SiO_3) biostimulant Optysil at 0.50 $dm^3 \cdot ha^{-1}$, applied in the leaf development stage (BBCH 14–16), significantly improved the growth and productivity of early crop potatoes. This study's results provided data for recommendations for foliar silicon application in early crop potato culture. However, future studies are necessary to optimize silicon source and concentration for different potato cultivars and environmental conditions, to achieve the expected benefits for farmers.

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