EFFECT OF SILICON FOLIAR APPLICATION ON THE ASSIMILATION AREA AND PHOTOSYNTHETIC PIGMENT CONTENTS OF POTATO (*SOLANUM TUBEROSUM* L.)

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(Received 27th Sep 2021; accepted 22nd Dec 2021)

Abstract. The effect of silicon-based biostimulant Optysil (200 g SiO_2 and 24 g Fe in 1 dm^3) on the assimilation area and photosynthetic pigment contents of potato was investigated. Optysil was applied once at the leaf development stage (BBCH 14-16) or at the tuber initiation stage (BBCH 40-41) and twice at the leaf development and tuber initiation stages, at the dose of 0.25 dm^3 ha^{-1} or 0.50 dm^3 ha^{-1} in each treatment. Optysil resulted in an enlargement of assimilation area and an increase in leaf area index (LAI), leaf dry weight, chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*) and carotenoids (Car) contents, and decreased the Chl *a*/Chl *b* ratio under water deficit conditions, but had no effect on the specific leaf area (SLA) and Chl (*a* + *b*)/Car ratio. Under periodical water deficits during potato growth, the plants produced the largest assimilation area with two Optysil applications at 0.50 dm^3 ha^{-1}, whereas the biosynthesis of photosynthetic pigments was most stimulated by Optysil at 0.25 dm^3 ha^{-1} applied at the tuber initiation stage. Under drought conditions, leaf growth was most stimulated by Optysil application at 0.50 dm^3 ha^{-1} at the initial potato growth period, whereas the biosynthesis of photosynthetic pigments by the double Optysil application at 0.50 dm^3 ha^{-1}.
Keywords: *sodium silicate, leaf area index (LAI), specific leaf area (SLA), chlorophyll a, chlorophyll b, carotenoids*

Introduction

Potato (*Solanum tuberosum* L.) growth is influenced by many biotic and abiotic stresses. Among abiotic stresses, drought is one of the most serious regarding potato growth and productivity. The most sensitive periods for water shortage are the vegetative and tuberization stage (Wagg et al., 2021). Periods of high temperature and drought are becoming more frequent in Central Europe, South-Central Asia, southeastern South America and the southeastern United States (Carrão et al., 2016). Under climate change conditions, biostimulants play an important role in mitigating abiotic stresses in plants. These products contain organic (seaweed extracts, humic substances, hydrolyzed proteins, amino acids containing products, microorganisms) or inorganic (Ti, Se, Si) compounds which enhance nutrient use efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrient content (du Jardin, 2015; Van Oosten et al., 2017; Bulgari et al., 2019; Drobek et al., 2019). In recent years, the use of silicon (Si) as a biostimulant has been increasing. Silicon plays an important role in plant growth by regulating both physiological and biochemical processes and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2002_13691384

mitigating biotic and abiotic stresses. Silicon stimulates plant growth in a species-specific manner. It can influence water relations and nutrient uptake, increase the content of photosynthetic pigments and regulate the activities of certain photosynthetic enzymes, as well as increase photosynthesis rate and decrease oxidative stress (Balakhnina and Borkowska, 2013; Zhu and Gong, 2014; Cao et al., 2015; Savvas and Ntatsi, 2015; Cooke and Leishman, 2016; Yavaş and Ünay, 2017; Zargar et al., 2019). Foliar application of silicon increases chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*) and carotenoids (Car) content in sweet pepper, onion, wheat and canola leaves (Lobato et al., 2009; Maghsoudi et al., 2016; Rangwala et al., 2019; Abdelaal et al., 2020; Bukhari et al., 2020) and Chl *a* and Chl *b* content in tomato and cucumber leaves (Abd El-Aziz, 2020; Gou et al., 2020). Since silicon plays an important role in mitigating biotic and abiotic stresses, silicon application is recommended for the improvement of vegetable crop production (Kaushik and Saini, 2019).

To date, few studies have focused on the effect of silicon foliar application on assimilation area and photosynthetic pigment contents in potato plants. A greenhouse pot experiment showed that both soil (soluble $SiO_2 \cdot HO_2$) and foliar (soluble concentrate stabilized silicic acid) application of silicon caused enlargement of leaf area and increased specific leaf area (SLA), as well as Chl *a* and Car contents in potato leaves, but had no effect on Chl *b* content. Silicon applied only to the soil increased dry weight of leaves. Silicon application alleviated water-deficit stress in potato. Chl *a* and Car concentrations, Chl *a*/Chl *b* ratio and tuber yield of water-deficit plants treated with silicon were similar to well-watered plants (Pilon et al., 2013, 2014). Another a greenhouse experiment showed that silicon ($NaSiO_3$) added to a nutrient solution caused enlargement of leaf area, and increased the leaf number and biomass of potato grown in a hydroponic system (Dorneles et al., 2018). Knowledge is scarce on the effect of silicon on potato growth under field conditions. A one-year field experiment carried out in Iran showed that foliar application of silicon (silica SiO_2 or sodium silicate nanoparticles Nano-$NaSiO_3$) enhanced the quantum yield of photosystem II (PS II) and Car content in potato leaves under salinity stress, but had no effect on Chl *a* and Chl *b* content. Under non-stress conditions, foliar application of silicon (sodium silicate nanoparticles Nano-$NaSiO_3$) increased Chl *a* and Chl *b* content, but had no effect on Chl *a*/Chl *b* ratio and Car content (Kafi et al., 2019). Silicon stimulated potato growth only at low doses. A higher concentrations of silicon in a nutrient solution induced reduction in potato growth parameters, mainly in leaf area (Dorneles et al., 2018). The excess of silicon on leaf surface may reduce transpiration so that it reduces photosynthesis (Hodson et al., 2005; Farooq and Dietz, 2015). The excess of silicon may also lead to the immobilization of essential elements for plant growth (Mg, Zn, Fe, Mo) in the apoplast (Moussa, 2006; Farooq and Dietz, 2015). Foliar application of silicon is effective only at very low doses and when started early in the vegetative stage (Laane, 2017). In the current study, it was hypothesized that silicon foliar application could contribute to enhancing assimilation area and photosynthetic pigment contents in potato under abiotic stress. The assumption was also made that potato response to silicon depends on the dose and time of application. The current study aimed to determine the effect of the dose and time of silicon foliar application on the assimilation area and photosynthetic pigment contents in potato leaves.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2002_13691384

Materials and methods

Experimental site and season

A field experiment was carried out in central-eastern Poland (52°03´N, 22°33´E), over three growing seasons (2016-2018). The experiment was located on soil classified as Haplic Luvisol (LV-ha) with a sandy loam texture (WRB FAO, 2015), with an acid-to-slightly-acid reaction (pH_{KCl} 5.2–5.6). The content of available phosphorus in the soil ranged from 97 to 114 mg P kg^{-1}, potassium from 93 to 124 mg K kg^{-1} and magnesium from 23 to 42 mg Mg kg^{-1} of soil.

Over the three years of the study, the most favorable hydrothermal conditions for the early crop potato culture were in the warm and moderately wet growing season of 2017 (*Table 1*). The year 2016 was warm with drought periods during potato growth, whereas 2018 was warm and very dry. In 2016 total precipitation in May was similar and in June over 40% lower than long-term average. In 2018 total precipitation in May and June was 2 times lower than the long-term average.

Table 1. *Mean air temperature and precipitation total in potato growing period recorded at the meteorological station of the Siedlce University of Natural Sciences and Humanities*

Years	Temperature; °C			Rainfalls; mm		
	April	May	June	April	May	June
2016	9.1	15.1	18.4	28.7	54.8	36.9
2017	6.9	13.9	17.8	59.6	49.5	57.9
2018	13.1	17.0	18.3	34.5	27.3	31.5
Many-year mean (1981-2010)	8.3	12.2	16.8	41.2	53.0	63.8

Plant material and experimental design

In this experiment, the silicon (Si) source was the liquid biostimulant Optysil (Intermag Ltd. Olkusz, Poland), which activates natural plant defense mechanisms against stress and stimulates their growth and development. 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 recommended dosage of the Optysil for potato harvested when fully ripe is 0.5 dm^3 ha^{-1} at the beginning of tuber formation stage and a repeat the treatment when tubers reach 70-80% of the final mass, and the optional 0.50 dm^3 ha^{-1} at the beginning of plant growth.

The effect of dose and time of Optysil application on the assimilation area and photosynthetic pigment contents in potato leaves were determined. The field experiment was established as a split-plot design with a control object without Optysil with three replications. The main plots were Optysil dose: 0.25 dm^3 ha^{-1} and 0.50 dm^3 ha^{-1}, and the sub plots time of Optysil application: the leaf development stage – according to the Biologische Bundesanstalt, Bundessortenamt and Chemical Industry (BBCH) the 14-16 stage, tuber initiation stage – BBCH 40-41, at both the 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 one plot-size control was located between main plots containing three sub plots.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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The drought-sensitive very early potato cultivar Catania (Europlant Pflanzenzucht GmbH, Germany) registered on the Common Catalogue of Varieties of Agricultural Plant Species (CCV) was grown. It is one of the most widely grown very early potato cultivars in central-eastern Poland.

At the tuber formation stage (BBCH 46-48), the assimilation leaf area, leaf dry weight, leaf area index (LAI) and specific leaf area (SLA) and photosynthetic pigment (Chl and Car) contents were determined. The measurements were made on four successive randomized plants per plot. The assimilation leaf area was measured by the weight method based on the weight of pieces with a known diameter and total weight of leaves per plant (Wadas and Kalinowski, 2017). LAI and SLA were calculated as the ratio of the assimilation leaf area/ground area and the ratio of assimilation leaf area/dry weight of leaves, respectively (Pietkiewicz, 1985). The relationship between the tuber weight per plant and the assimilation area and photosynthetic pigment contents were also determined. The tuber weight per plant were determined on ten successive plants per plot.

Agrotechnics and plant protection

In each year of the study, spring triticale was grown as a potato forecrop. Potato cultivation was carried out according to common agronomical practices. Farmyard manure was applied in autumn at the 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 sulphate) per hectare in spring.

Six-week pre-sprouted seed potatoes were planted on 6 April 2016, 10 April 2017 and 9 April 2018, with a row spacing of 25 cm and 67.5 cm between rows (96 plants per plot). Potatoes were harvested 75 days after planting (the end of June).

Colorado potato beetle (*Leptinotarsa decemlineata*) was controlled using thiamethoxam (Actara 25 WG; Syngenta Crop Protection AG Basel, Switzerland).

Determination of photosynthetic pigment content

The photosynthetic pigment (Chl *a*, Chl *b*, Car) contents were determined in the youngest fully expanded leaves, i.e. the fourth and fifth leaves from the top, by the Arnon method (Arnon, 1949). The photosynthetic pigments were extracted by 80% acetone in 2 g fresh leaves and absorbance was measured at the 663 nm, 645 nm and 470 nm wavelengths, respectively, for Chl *a*, Chl *b* and Car using a UV-1800 spectrophotometer (Rayleigh, UK). Chl *a*, Chl *b*, Chl (*a* + *b*) and Car contents were calculated by using the following formulas (*Eqs. 1-4*):

$$Chl\ a = \frac{(12.7\,A663 - 2.7A645)V}{1000W} \quad \text{(Eq.1)}$$

$$Chl\ b = \frac{(22.9A645 - 4.7A663)V}{1000W} \quad \text{(Eq.2)}$$

$$Chl\ (a+b) = \frac{(20.2A645 + 8.02A663)V}{1000W} \quad \text{(Eq.3)}$$

$$Car = 1000A470 - 2.27Chl\ a - \frac{81.4Chl\ b}{227} \quad \text{(Eq.4)}$$

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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where: A – absorbance at specific wavelength; V– volume of the extract (cm^3); W – weight of the leaves used for extraction (g).

The contents of photosynthetic pigments were expressed as milligrams per gram of the fresh weight of potato leaves. The ratios of Chl *a*/Chl *b* and Chl (*a* + *b*)/Car were also calculated.

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 (Optysil dose × time of Optysil application × years) with a control object. The analysis of the results of the study was conducted using the orthogonal contrast to compare the control without Optysil with the test objects with Optysil. Fisher-Snedecor *F* test was used to check the significance of sources of variability, and Tukey's test was used to check the significance of differences between compared averages at $p \leq 0.05$. Calculations were performed using Statistica 12 PL software (StatSoft, Tulsa, OK, USA). Results are shown as mean ± standard deviation (SD). The linear correlation was used to determine relationship between the tuber weight and, assimilation area and photosynthetic pigment contents in potato leaves ($n = 21$).

Results

Assimilation area and dry weight of leaves

Silicon-based biostimulant Optysil caused enlargement of the assimilation area and increased dry weight of leaves but had no effect on the SLA (*Table 2*). Optysil effect depended on the weather conditions during potato growth. Optysil had a significant effect on the assimilation area and dry weight of leaves under water deficit conditions in the years 2016 and 2018. In the warm growing season of 2016 with periodical water deficits, Optysil caused enlargement of assimilation area on average by 578 cm^2 (14%) and increased leaf dry weight by 4.79 g (23%) compared with the control plants. As a result, the LAI for the treated plants was higher on average by 0.34 than for control plants. In the warmer and very dry growing season of 2018, following application of Optysil, the assimilation area was larger on average by 327 cm^2 (9%), LAI value was higher by 0.19 and leaf dry weight by 1.84 g (11%) compared with the control plants.

The dose and time of Optysil application had a significant effect on the assimilation area but had no effect on the leaf dry weight (*Tables 3* and *4*). The study demonstrated the significant effect of the interaction of the years and the dose of Optysil and the interaction of the years and the time of Optysil application on the assimilation area.

The Optysil dose had a significant effect on the assimilation area only in the warm and very dry growing season of 2018 (*Table 3*). In that year, after the application of 0.50 $dm^3\ ha^{-1}$ of Optysil, the assimilation area was larger on average by 534 cm^2 (12%) and LAI was higher by 0.32 as compared with the values at the dose of 0.25 $dm^3\ ha^{-1}$. The time of Optysil application had a significant effect on the assimilation area in 2016 with the lower water deficit than in 2018 (*Table 4*). Regardless of Optysil dose, in 2016, the assimilation area was the largest with two Optysil applications, at the leaf development stage and with a repeated treatment at the tuber initiation stage (BBCH 14-16 and BBCH 40-41).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Table 2. *Effect of Optysil on assimilation area and dry weight of leaves*

Treatment	Years			Mean
	2016	2017	2018	
Assimilation area; cm^2				
Without Optysil	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 area index (LAI); cm^2 cm^2				
Without Optysil	2.51 ± 0.02 b	3.56 ± 0.06 a	2.12 ± 0.02 b	2.73 ± 0.65 b
With Optysil	2.85 ± 0.34 a	3.43 ± 0.53 a	2.31 ± 0.23 a	2.86 ± 0.59 a
Leaf dry weight; g				
Without Optysil	20.97 ± 2.52 b	22.93 ± 3.01 a	16.57 ± 1.53 b	20.16 ± 3.20 b
With Optysil	25.76 ± 3.10 a	23.37 ± 3.26 a	18.41 ± 2.02 a	22.51 ± 4.17 a
Specific leaf area (SLA); cm^2 g^{-1}				
Without Optysil	202.2 ± 14.6 a	264.4 ± 14.3 a	216.8 ± 15.0 a	227.8 ± 30.03 a
With Optysil	187.7 ± 9.9 a	246.9 ± 19.4 a	211.5 ± 10.7 a	215.4 ± 28.12 a

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

Table 3. *Effect of Optysil dose on assimilation area and dry weight of leaves*

Optysil dose	Years			Mean
	2016	2017	2018	
Assimilation area; cm^2				
0.25 dm^3 ha^{-1}	4718 ± 440 a	5865 ± 904 a	3631 ± 228 b	4738 ± 1091 b
0.50 dm^3 ha^{-1}	4918 ± 685 a	5704 ± 931 a	4165 ± 306 a	4929 ± 922 a
Leaf area index (LAI); cm^2 cm^2				
0.25 dm^3 ha^{-1}	2.79 ± 0.26 a	3.47 ± 0.53 a	2.15 ± 0.16 b	2.81 ± 0.64 b
0.50 dm^3 ha^{-1}	2.91 ± 0.40 a	3.38 ± 0.55 a	2.47 ± 0.18 a	2.92 ± 0.54 a
Leaf dry weight; g				
0.25 dm^3 ha^{-1}	25.32 ± 3.38 a	23.14 ± 3.54 a	17.46 ± 1.68 a	21.97 ± 4.43 a
0.50 dm^3 ha^{-1}	26.21 ± 2.91 a	23.59 ± 3.16 a	19.37 ± 1.96 a	23.06 ± 3.89 a

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

The study demonstrated the significant effect of the interaction of the years, the dose and the time of Optysil application on the assimilation area (*Table 5*). In 2016 with drought periods during potato growth, the plants produced the largest assimilation area with two Optysil applications at 0.50 dm^3 ha^{-1}, at the leaf development stage and with a repeated treatment at the tuber initiation stage (BBCH 14-16 and BBCH 40-41). In the very dry growing season of 2018, the assimilation area was largest after the application of 0.50 dm^3 ha^{-1} of Optysil at the leaf development stage (BBCH 14-16).

Photosynthetic pigment contents

Silicon-based biostimulant Optysil had a significant effect on photosynthetic pigment contents in potato leaves under water deficit conditions in the years 2016 and 2018 (*Table 6*). In the warm growing season of 2016 with periodical water deficits, Optysil

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increased leaf Chl *a* content on average by 0.055 mg g^{-1} (11%) compared with the control plants but had no effect on the Chl *b* or Car contents. As a result, the Chl *a*/Chl *b* ratio was higher than in the control plants, whereas the Chl (*a* + *b*)/Car ratio did not differ significantly. In the warmer and very dry growing season of 2018, following the application of Optysil, the leaf Chl *a* content was higher on average by 0.167 mg g^{-1} (35.5%), Chl *b* by 0.108 mg g^{-1} (54%) and Car by 0.007 mg g^{-1} (43.8%) compared with the control plants. In that year, Optysil caused a decrease in the Chl *a*/Chl *b* ratio but had no effect on the Chl (*a* + *b*)/Car ratio.

Table 4. *Effect of time of Optysil application on assimilation area and dry weight of leaves*

Time of Optysil application	Years			Mean
	2016	2017	2018	
Assimilation area; cm^2				
Leaf development stage	4776 ± 494 b	5825 ± 833 a	4103 ± 436 a	4901 ± 929 ab
Tuber initiation stage	4325 ± 393 b	5764 ± 414 a	3801 ± 181 a	4630 ± 914 b
Leaf development and tuber initiation stages	5352 ± 250 a	5763 ± 679 a	3791 ± 439 a	4969 ± 1176 a
Leaf area index (LAI); cm^2 cm^2				
Leaf development stage	2.83 ± 0.29 b	3.34 ± 0.50 a	2.44 ± 0.26 a	2.90 ± 0.55 a
Tuber initiation stage	2.56 ± 0.26 b	3.42 ± 0.25 a	2.26 ± 0.11 a	2.74 ± 0.54 b
Leaf development and tuber initiation stages	3.17 ± 0.16 a	3.42 ± 0.80 a	2.25 ± 0.26 a	2.94 ± 0.69 a
Leaf dry weight; g				
Leaf development stage	24.66 ± 2.73 a	23.22 ± 3.99 a	18.80 ± 2.22 a	22.23 ± 4.04 a
Tuber initiation stage	23.86 ± 2.01 a	23.57 ± 1.87 a	18.12 ± 2.41 a	21.85 ± 7.49 a
Leaf development and tuber initiation stages	28.74 ± 2.15 a	23.35 ± 4.09 a	18.32 ± 1.70 a	23.46 ± 4.52 a

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

Table 5. *Interaction effect of years, dose and time of Optysil application on assimilation area*

Time of Optysil application	Years and Optysil dose					
	2016		2017		2018	
	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}
Assimilation area; cm^2						
Leaf development stage	4473 ± 352 b	5119 ± 366 a	5977 ± 381 a	5673 ± 242 a	3813 ± 247 ab	4393 ± 401 a
Tuber initiation stage	4509 ± 289 b	4141 ± 448 b	5666 ± 217 a	5862 ± 489 a	3678 ± 200 ab	3923 ± 164 ab
Leaf development and tuber initiation stages	5210 ± 236 a	5493 ± 280 a	5952 ± 553 a	5576 ± 290 a	3403 ± 184 b	4180 ± 247 a
Leaf area index (LAI) cm^2 cm^2						
Leaf development stage	2.62 ± 0.21 b	3.03 ± 0.22 a	3.54 ± 0.22 a	3.36 ± 0.15 a	2.28 ± 0.15 ab	2.61 ± 0.24 a
Tuber initiation stage	2.67 ± 0.17 b	2.45 ± 0.26 b	3.36 ± 0.13 a	3.47 ± 0.29 a	2.18 ± 0.12 ab	2.33 ± 0.10 ab
Leaf development and tuber initiation stages	3.09 ± 0.14 a	3.25 ± 0.16 a	3.53 ± 0.32 a	3.30 ± 0.17 a	2.06 ± 0.11 b	2.48 ± 0.15 a

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

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2002_13691384

Table 6. *Effect of Optysil on photosynthetic pigment contents*

Treatment	Years			Mean
	2016	2017	2018	
Chlorophyll *a* (Chl *a*); mg g^{-1}				
Without Optysil	0.490 ± 0.010 b	0.716 ± 0.094 a	0.470 ± 0.024 b	0.558 ± 0.128 a
With Optysil	0.545 ± 0.079 a	0.661 ± 0.064 a	0.637 ± 0.105 a	0.614 ± 0.096 a
Chlorophyll *b* (Chl *b*); mg g^{-1}				
Without Optysil	0.209 ± 0.008 a	0.447 ± 0.092 a	0.200 ± 0.010 b	0.285 ± 0.130 a
With Optysil	0.216 ± 0.042 a	0.410 ± 0.069 a	0.308 ± 0.069 a	0.311 ± 0.100 a
Chl (*a* + *b*); mg g^{-1}				
Without Optysil	0.700 ± 0.028 b	1.164 ± 0.180 a	0.671 ± 0.026 b	0.845 ± 0.256 a
With Optysil	0.761 ± 0.118 a	1.072 ± 0.101 a	0.946 ± 0.166 a	0.926 ± 0.182 a
Carotenoids (Car); mg g^{-1}				
Without Optysil	0.016 ± 0.001 a	0.030 ± 0.007 a	0.016 ± 0.001 b	0.021 ± 0.008 a
With Optysil	0.018 ± 0.002 a	0.032 ± 0.003 a	0.023 ± 0.004 a	0.024 ± 0.007 a
Chl *a*/Chl *b*				
Without Optysil	2.349 ± 0.116 b	1.620 ± 0.184 a	2.342 ± 0.108 a	2.104 ± 0.383 a
With Optysil	2.546 ± 0.177 a	1.648 ± 0.253 a	2.105 ± 0.252 b	2.100 ± 0.435 a
Chl (*a* + b)/Car				
Without Optysil	43.44 ± 0.85 a	38.50 ± 2.47 a	42.75 ± 1.75 a	41.56 ± 2.78 a
With Optysil	41.80 ± 2.24 a	33.12 ± 2.50 a	42.09 ± 3.73 a	39.01 ± 5.08 a

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

The study demonstrated the significant effect of the interaction of the years and the dose of Optysil and the interaction of the years and the time of Optysil application on the photosynthetic pigment contents (*Tables 7* and *8*).

Table 7. *Effect of Optysil dose on photosynthetic pigment contents*

Optysil dose	Years			Mean
	2016	2017	2018	
Chlorophyll *a* (Chl *a*); mg g^{-1}				
0.25 dm^3 ha^{-1}	0.568 ± 0.076 a	0.679 ± 0.058 a	0.609 ± 0.067 b	0.619 ± 0.080 a
0.50 dm^3 ha^{-1}	0.522 ± 0.079 a	0.644 ± 0.064 a	0.665 ± 0.131 a	0.610 ± 0.111 a
Chlorophyll *b* (Chl *b*); mg g^{-1}				
0.25 dm^3 ha^{-1}	0.228 ± 0.051 a	0.396 ± 0.064 a	0.278 ± 0.043 b	0.300 ± 0.088 a
0.50 dm^3 ha^{-1}	0.204 ± 0.031 a	0.424 ± 0.076 a	0.338 ± 0.079 a	0.322 ± 0.112 a
Chl (*a* + *b*); mg g^{-1}				
0.25 dm^3 ha^{-1}	0.796 ± 0.124 a	1.076 ± 0.108 a	0.888 ± 0.104 b	0.920 ± 0.161 a
0.50 dm^3 ha^{-1}	0.736 ± 0.108 a	1.068 ± 0.099 a	1.004 ± 0.201 a	0.933 ± 0.505 a
Carotenoids (Car); mg g^{-1}				
0.25 dm^3 ha^{-1}	0.018 ± 0.002 a	0.030 ± 0.004 a	0.021 ± 0.002 b	0.024 ± 0.007 a
0.50 dm^3 ha^{-1}	0.018 ± 0.003 a	0.032 ± 0.002 a	0.024 ± 0.005 a	0.025 ± 0.007 a
Chl *a*/Chl *b*				
0.25 dm^3 ha^{-1}	2.532 ± 0.214 a	1.774 ± 0.236 a	2.213 ± 0.240 a	2.163 ± 0.391 a
0.50 dm^3 ha^{-1}	2.560 ± 0.141 a	1.552 ± 0.243 a	1.997 ± 0.260 a	2.037 ± 0.471 a

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

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Table 8. *Effect of time of Optysil application on photosynthetic pigment contents*

Time of Optysil application	Years			Mean
	2016	2017	2018	
Chlorophyll *a* (Chl *a*); mg g^{-1}				
Leaf development stage	0.540 ± 0.048 ab	0.658 ± 0.070 a	0.582 ± 0.098 b	0.593 ± 0.086 a
Tuber initiation stage	0.606 ± 0.079 a	0.637 ± 0.036 a	0.630 ± 0.045 ab	0.624 ± 0.055 a
Leaf development and tuber initiation stages	0.488 ± 0.066 b	0.688 ± 0.083 a	0.698 ± 0.133 a	0.625 ± 0.114 a
Chlorophyll *b* (Chl b); mg g^{-1}				
Leaf development stage	0.205 ± 0.020 a	0.397 ± 0.107 a	0.272 ± 0.044 b	0.294 ± 0.101 a
Tuber initiation stage	0.224 ± 0.057 a	0.415 ± 0.040 a	0.320 ± 0.082 a	0.327 ± 0.092 a
Leaf development and tuber initiation stages	0.205 ± 0.023 a	0.418 ± 0.054 a	0.331 ± 0.073 a	0.313 ± 0.110 a
Chl (*a* + *b*); mg g^{-1}				
Leaf development stage	0.754 ± 0.064 ab	1.576 ± 0.142 a	0.855 ± 0.138 b	0.889 ± 0.258 a
Tuber initiation stage	0.852 ± 0.132 a	1.053 ± 0.048 a	0.951 ± 0.124 ab	0.952 ± 0.132 a
Leaf development and tuber initiation stages	0.678 ± 0.089 b	1.108 ± 0.099 a	1.031 ± 0.203 a	0.939 ± 0.233 a
Carotenoids (Car); mg g^{-1}				
Leaf development stage	0.018 ± 0.002 a	0.031 ± 0.003 a	0.021 ± 0.003 a	0.023 ± 0.006 a
Tuber initiation stage	0.020 ± 0.002 a	0.032 ± 0.001 a	0.022 ± 0.001 a	0.025 ± 0.009 a
Leaf development and tuber initiation stages	0.016 ± 0.002 a	0.034 ± 0.003 a	0.024 ± 0.006 a	0.025 ± 0.007 a
Chl *a*/Chl *b*				
Leaf development stage	2.540 ± 0.126 a	1.736 ± 0.383 a	2.145 ± 0.204 a	2.140 ± 0.417 a
Tuber initiation stage	2.516 ± 0.276 a	1.550 ± 0.182 a	2.048 ± 0.382 a	2.038 ± 0.716 a
Leaf development and tuber initiation stages	2.584 ± ± 0.105 a	1.659 ± 0.126 a	2.122 ± 0.151 a	2.122 ± 0.407 a

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

The Optysil dose had a significant effect on the leaf photosynthetic pigment contents only in the warm and very dry growing season of 2018 (*Table 7*). In that year, after the application of 0.50 dm^3 ha^{-1} of Optysil, the Chl *a* content was higher on average by 0.056 mg g^{-1} (9%), Chl *b* by 0.060 mg g^{-1} (21.6%) and Car by 0.003 mg g^{-1} (14%) as compared with the values at the dose of 0.25 dm^3 ha^{-1}. The Optysil dose had no effect on the Chl *a*/Chl *b* ratio. Time of Optysil application had a significant effect on the leaf photosynthetic pigment contents under water deficit conditions in the years 2016 and 2018 (*Table 8*). In 2016 with the lower water deficit, the Chl *a* and Chl *b* contents were the highest with a single application of Optysil at the tuber initiation stage (BBCH 40-41) whereas during the very dry growing season of 2018, the contents of Chl *a* and Chl *b* were the highest with two Optysil applications, at the leaf development stage and with a repeated treatment at the tuber initiation stage (BBCH 14-16 and BBCH 40-41). The time of Optysil application had no effect on the Chl *a*/Chl *b* ratio.

The study demonstrated the significant effect of the interaction of the years, the dose and the time of Optysil application on the leaf photosynthetic pigment contents (*Table 9*). In 2016 with drought periods during potato growth, the Chl *a*, Chl *b* and Car

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DOI: http://dx.doi.org/10.15666/aeer/2002_13691384

contents were the highest after the application of 0.25 dm^3 ha^{-1} of Optysil at the tuber initiation stage (BBCH 40-41). In the very dry growing season of 2018, the content of these pigments was highest after the application of 0.50 dm^3 ha^{-1} of Optysil at the leaf development stage (BBCH 14-16) and with a repeated treatment at the tuber initiation stage (BBCH 40-41) with the same dose of Optysil.

Table 9. *Interaction effect of years, dose and time of Optysil application on photosynthetic pigment contents*

Time of Optysil application	Years and Optysil dose					
	2016		2017		2018	
	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}	0.25 dm^3 ha^{-1}	0.50 dm^3 ha^{-1}
Chlorophyll *a* (Chl *a*); mg g^{-1}						
Leaf development stage	0.506 ± 0.023 b	0.575 ± 0.040 ab	0.676 ± 0.086 a	0.640 ± 0.062 a	0.621 ± 0.095 b	0.543 ± 0.103 b
Tuber initiation stage	0.655 ± 0.068 a	0.557 ± 0.061 ab	0.640 ± 0.036 a	0.634 ± 0.043 a	0.607 ± 0.016 b	0.653 ± 0.059 ab
Leaf development and tuber initiation stages	0.543 ± 0.016 ab	0.433 ± 0.042 b	0.720 ± 0.014 a	0.657 ± 0.104 a	0.599 ± 0.093 b	0.798 ± 0.074 a
Chlorophyll *b* (Chl *b*); mg g^{-1}						
Leaf development stage	0.198 ± 0.008 a	0.228 ± 0.014 a	0.344 ± 0.063 a	0.450 ± 0.082 a	0.288 ± 0.048 ab	0.256 ± 0.042 b
Tuber initiation stage	0.278 ± 0.065 a	0.213 ± 0.027 a	0.396 ± 0.023 a	0.433 ± 0.049 a	0.256 ± 0.015 b	0.384 ± 0.067 a
Leaf development and tuber initiation stages	0.208 ± 0.011 a	0.171 ± 0.014 a	0.447 ± 0.062 a	0.388 ± 0.032 a	0.288 ± 0.062 ab	0.374 ± 0.061 a
Chll (*a* + *b*); mg g^{-1}						
Leaf development stage	0.704 ± 0.031 ab	0.804 ± 0.045 ab	1.022 ± 0.146 a	1.091 ± 0.160 a	0.910 ± 0.136 b	0.800 ± 0.141 b
Tuber initiation stage	0.934 ± 0.126 a	0.771 ± 0.087 ab	1.037 ± 0.026 a	1.068 ± 0.066 a	0.864 ± 0.015 b	1.038 ± 0.125 ab
Leaf development and tuber initiation stages	0.750 ± 0.027 ab	0.605 ± 0.055 b	1.169 ± 0.074 a	1.046 ± 0.089 a	0.888 ± 0.154 b	1.174 ± 0.135 a
Carotenoids (Car); mg g^{-1}						
Leaf development stage	0.016 ± 0.001 ab	0.019 ± 0.002 ab	0.031 ± 0.004 a	0.031 ± 0.001 a	0.021 ± 0.003 b	0.020 ± 0.004 b
Tuber initiation stage	0.022 ± 0.002 a	0.019 ± 0.002 ab	0.032 ± 0.001 a	0.031 ± 0.002 a	0.022 ± 0.001 b	0.023 ± 0.002 b
Leaf development and tuber initiation stages	0.018 ± 0.001 ab	0.015 ± 0.001 b	0.036 ± 0.002 a	0.032 ± 0.002 a	0.019 ± 0.002 b	0.030 ± 0.004 a

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

Relationship between tuber weight and, assimilation area and photosynthetic pigment contents in potato leaves

The yield-forming effect of Optysil depended on water conditions during the potato growth period (*Table 10*). In the 2016 with a drought periods during potato growth, with the use of Optysil the average tuber weight per plant was higher by 83.0 g (23%) compared with the cultivation without biostimulant. In very dry growing season of 2018, following the application of Optysil the average tuber weight per plant was higher by 22.3 g (13%). A significant positive correlation was found between the tuber weight per plant and assimilation area and dry weight of leaves (*Table 11*). The tuber weight was not significantly correlated with photosynthetic pigment contents.

Table 10. *Effect of Optysil on tuber weight per plant; g*

Treatment	Years			Mean
	2016	2017	2018	
Without Optysil	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 ± 30.3 a	193.0 ± 29.4 a	354.0 ± 119.7 a

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

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Table 11. *Linear correlation coefficients (n = 21) between tuber weight and assimilation area, leaf dry weight and photosynthetic pigment contents*

Specification	Correlation coefficient
Assimilation area	0.6719*
Leaf dry weight	0.7973*
Leaf area index (LAI)	0.6695*
Specific leaf area (SLA)	0.0986
Chlorophyll *a* (Chl *a*)	-0.0773
Chlorophyll *b* (Chl *b*)	0.1092
Chl (*a* + *b*)	0.0507
Carotenoids (Car)	0.2290

*Significant at $p \leq 0.05$

Discussion

Assimilation area and photosynthetic pigment contents are important parameters of assessment plant growth. Previously, a greenhouse pot experiment showed that three times (10, 20 and 30 days after emergence) silicon foliar application (1.425 mM Si water solution of soluble concentrate stabilized silicic acid) caused enlargement of the leaf area and increased SLA of very early potato cultivar Agata (resistant to a short-term drought) on Typic Acrortox soil, but had no effect on the dry weight of leaves (Pilon et al., 2013). In the present study, the silicon-based (Na_2SiO_3) biostimulant Optysil caused enlargement of the assimilation area and increased leaf dry weight of drought-sensitive very early potato cultivar Catania under water deficit on Haplic Luvisol soil, but had no effect on the SLA. The enlargement of assimilation area does not always results in an increase in the tuber yield. The relationship between the rate of tuber yield and LAI value is rather complex, because potato responds very sensitively to weather changes during vegetation that may cause the falling or new growth of leaves (Zrůst et al., 1999). According to Howlander and Hoque (2018), LAI increases progressively over time, reaching a peak at 60 days after potato planting and thereafter declining. The LAI describes the growth in lowland fields, whereas the growth of individual plants is characterized by the SLA (Van Delden et al., 2000). The SLA for potato depends on the growth stage and temperature (Howlander and Hoque, 2018; Van Delden et al., 2000).

Silicon stimulated potato growth only at low doses. A higher concentration of silicon in a nutrient solution induced reduction in potato leaf area (Dorneles et al., 2018). In the present study, the effect of dose and time of Optysil application on assimilation area depended on a water deficit during potato growth. Under conditions of periodical water deficits during potato growth, the plants produced a largest assimilation area with two Optysil applications at 0.50 dm^3 ha^{-1}, at the leaf development stage and with a repeated treatment at the tuber initiation stage (BBCH14-16 and BBCH 40-41). Under drought conditions, growth of leaves was most stimilated by Optysil application at 0.50 dm^3 ha^{-1} only at the initial potato growth period (BBCH14-16).

There is scarce knowledge of the effect of silicon foliar application on the biosynthesis of photosynthetic pigments by potato plants. Photosynthetic pigment contents and their ratios may be used as an indicator of plant response to environmental conditions (Strzałka et al., 2003; Zhou et al., 2019). Chlorophyll concentration in leaves is an indicator of potato tuber yield under water-shortage conditions (Ramírez et al.,

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2014). A greenhouse pot experiment showed that five-times (10, 20, 30, 40 and 50 days after emergence) foliar application of silicon (1.425 mM Si water solution of soluble concentrate stabilized silicic acid) increased Chl *a* and Car content in leaves of very early potato cultivar Agata (resistant to a short-term drought) under water deficit conditions on Typic Acrortox soil, but had no effect on Chl *b* content (Pilon et al., 2014). Previously, a one-year field experiment carried out in Iran showed that two-time (40 and 50 days after potato planting) foliar application of silicon (1000 ppm silica SiO_2 or 400 ppm sodium silicate nanoparticles Nano-$NaSiO_3$) increased Chl *a* and Chl *b* content in leaves of medium late potato cultivar Agria (drought-resistant) on Silty Loam soil (Kafi et al., 2019), which is confirmed in the present study. Optysil increased Chl *a*, Chl *b* and Car contents in leaves of drought-sensitive very early potato cultivar Catania under water deficit on Haplic Luvisol soil. An increase in the Chl *a* and Chl *b* content following Optysil application resulted in a decrease in the Chl *a*/Chl *b* ratio compared with the control plants. Optysil had no significant effect on the Chl (*a* + *b*)/Car ratio in potato leaves. A decrease in the Chl *a*/Chl *b* ratio is the plants' response to abiotic stress (Sumanta et al., 2014). Silicon application is beneficial for plants under water deficit conditions (Bukhari et al., 2020), which is confirmed in the present study. A decrease in chlorophyll content under drought stress is associated with both a decrease in chlorophyll synthesis and an increase in the degradation of chlorophyll by chlorophyllase enzyme (Zahedi et al., 2019; Bukhari et al., 2020). Silicon mitigates the adverse effect of drought by inducing synthesis of new chlorophyll and protecting existing chlorophyll from oxidative stress induced by drought (Cao et al., 2015; Bukhari et al., 2020). The positive responses of photosynthetic pigments to silicon application under drought stress may be associated with a protective role of silicon on chloroplast ultrastructure (Cao et al., 2015; Savvas and Ntatsi, 2015) and increase activities of some antioxidant enzymes, such as superoxide dismutase (SOD) and catalase (CAT), that are located in the chloroplast. Catalase (CAT) is a principal enzyme that prevents chlorophyll degradation (Balakhnina and Borkowska, 2013; Pilon et al., 2014; Zhu and Gong, 2014; Savvas and Ntatsi, 2015; Bukhari et al., 2020).

There is a scarce knowledge of the effect of different doses and time of silicon foliar application on the biosynthesis of photosynthetic pigments by potato plants. Previous, a one-year field experiment carried out in Iran showed that two-times (40 and 50 days after potato planting) application of 400 ppm sodium silicate nanoparticles Nano-$NaSiO_3$ stimulated the biosynthesis of Chl *a*, Chl *b* and Car more strongly than 1000 ppm silica SiO_2 (Kafi et al., 2019). In the present study, the effect of dose and time of Optysil application on leaf photosynthetic pigment contents depended on a water deficit during potato growth. In a year with periodical water deficits during potato growth, an Optysil dose of 0.25 dm^3 ha^{-1} application at the tuber initiation stage (BBCH 40-41) stimulated the biosynthesis of Chl *a*, Chl *b* and Car in potato leaves more strongly than the dose of 0.50 dm^3 ha^{-1}. In a very dry year, the biosynthesis of photosynthetic pigments was most stimulated by two Optysil applications at 0.50 dm^3 ha^{-1}, at the initial plant growth stage (BBCH 14-16) and with a repeated treatment in the tuber initiation stage (BBCH 40-41).

The silicon-based biostimulant Optysil reduced drought stress and improved the yield of field crops (Ciecierski and Kardasz, 2014; Artyszak, 2018), which is confirmed in the present study. In the present study, following Optysil application, the tuber weight per plant of drought sensitive very early potato cultivar Catania 75 days after planting was higher, on average by 23% under periodical water deficits during potato

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growth, and by 13% under drought conditions. A significant positive correlation was found between the tuber weight and assimilation area, and leaf dry weight and LAI. A positive correlation between leaf area and tuber yield suggests thet the enlargement of leaf area could enhance the export of photosynthetic products and cause an increase in tuber yield (Li et al., 2013). According to Ascione et al. (2013), the tuber growth rate is only slightly corelated with LAI, and still less so with SLA, which is confirmed in the present study. No correlation was found between tuber weight and SLA, and between the tuber weight and photosynthetic pigment contents.

Conclusions

This study demonstrated possibility of silicon use to promote potato growth and biosynthesis of photosynthetic pigments under water deficit. Silicon-based biostimulant Optysil caused enlargement of assimilation area and increased the leaf dry weight, Chl *a*, Chl *b* and Car contents, and decreased the Chl *a*/Chl *b* ratio, but had no effect on the SLA and Chl (*a* + *b*)/Car ratio. Optysil effect depended on the dose and time of application. The dose and time of Optysil application had a greater effect on the assimilation area than on the leaf dry weight. Optysil at 0.50 dm^3 ha^{-1} stimulated biosynthesis of photosynthetic pigments more strongly than at 0.25 dm^3 ha^{-1}. The time of Optysil application had a greater effect on the Chl content than on the Car content.

Results of this study increased current knowledge to potato response on silicon foliar application under field conditions and provides data for future recommendations for silicon application in early crop potato culture. However, future studies are necessary to evaluate responses of various potato cultivars on silicon, and optimize dose and time of silicon application for environmental conditions to achieve the expected outputs.

Acknowledgements. This study was supported from the science grant granted by the Polish Ministry of Science and Higher Education under the statutory activities of the Siedlce University of Natural Sciences and Humanities (grant number 218/05/S). The authors wish to acknowledge the Intermag Ltd, Olkusz, Poland, for the biostimulant used for experiment.

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