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EFFECT OF TITANIUM ON ASSIMILATION LEAF AREA AND CHLOROPHYLL CONTENT OF VERY EARLY-MATURING POTATO CULTIVARS

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ABSTRACT

Background. Titanium applied via roots or leaves stimulates plant growth. Titanium exerts a favourable effect on plant growth only at low concentration, while at higher concentrations it may exhibit toxic effects. Determining the optimal doses and dates of titanium application are very important in the optimisation of early potato production.
Material and methods. The effect of dose (0.2 $dm^3 \cdot ha^{-1}$ or 0.4 $dm^3 \cdot ha^{-1}$) and date (leaf development stage – BBCH 14-16, tuber formation stage – BBCH 41-43, and at both leaf development stage and tuber formation stage) of a Tytanit® application (8.5 g Ti in 1 dm^3) on the assimilation leaf area and chlorophyll content of very early-maturing potato cultivars was investigated. The field experiment was established as a split-block-split-plot design with a control object without Tytanit®. The assimilation leaf area was measured by the weight method and the chlorophyll content was estimated using a chlorophyll meter SPAD-502.
Results. Tytanit® caused an enlargement of the assimilation leaf area and an increase in chlorophyll content in leaves, particularly under stress conditions. Under thermal and moisture conditions unfavourable for the growth of very early-maturing potato cultivars, a Tytanit® dose of 0.4 $dm^3 \cdot ha^{-1}$ stimulated the growth of leaves more strongly than a dose of 0.2 $dm^3 \cdot ha^{-1}$. The plants produced a greater assimilation leaf area when Tytanit® was only applied once, in the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). A double Tytanit® application resulted in a reduction in the assimilation leaf area compared with a single treatment. Following Tytanit® application, the leaf area index (LAI) averaged 4.13 and was higher by 0.42 compared with the cultivation without growth stimulant, while the specific leaf area (SLA) averaged 3.290 $m^2 \cdot kg^{-1}$ and was higher by 0.129 $m^2 \cdot kg^{-1}$ than in the cultivation without growth stimulant. The SLA was the highest when Tytanit® was only applied once in the tuber formation stage (BBCH 41-43). The dose and date of Tytanit® application slightly affected the leaf greenness index (SPAD).
Conclusion. The present study demonstrated the stimulating effects of titanium ions (Tytanit®) on the assimilation leaf area and chlorophyll biosynthesis in leaves of very-early maturing potato cultivars under stress conditions.

Key words: assimilation leaf area, leaf area index (LAI), leaf greenness index (SPAD), specific leaf area (SLA), Tytanit®

INTRODUCTION

Although titanium (Ti) is neither a major or minor nutrient for plants, it is classified as a beneficial element for plant growth (Pais *et al.*, 1991; Carvajal and Alcaraz, 1998). The titanium content in plants is low and ranges from 0.1 $mg \cdot kg^{-1}$ to 10 $mg \cdot kg^{-1}$ of dry matter (Tlustoš *et al.*, 2005). Titanium is present in

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soil mostly in the form of minerals as TiO_2 or $FeTiO_3$. In this form it is not bioassimilable. Titanium fertilizer applied via roots or leaves stimulates plant growth in a species-specific manner. It can stimulate the uptake of some nutrients for plants, and the activity of many enzymes (catalase, peroxidase, lipoxygenase and nitrogen reductase), as well as increase the chlorophyll content in plant leaves (Pais, 1983; Dumon and Ernst, 1988; Du *et al*., 2010). The effects of titanium depends on the plant species, plant age, and the tissue concentration of other minerals (Dumon and Ernst, 1988). A pot study carried out on Belgian sandy soil of pH 6.8 showed that foliar application of titanium, in either inorganic (titanium chloride, $TiCl_4$) or organic (dicyclopentadienyl titanium chloride, $C_{10}H_{10}Cl_2Ti$) form, in concentrations of 1 mg Ti in dm^{-3} increased the chlorophyll a, chlorophyll b and total chlorophyll contents in bean leaves and the uptake of major and trace elements (Ram *et al*., 1983). This suggests the possible role of titanium in promoting the photosynthetic activity of leaves. The increase in chlorophyll concentration after titanium application could be due to either a direct effect of titanium or an indirect effect caused by the increased concentration of magnesium and other elements in the leaves. The organic and inorganic forms of titanium have been found to be equally effective. A study carried out in China showed the growth--promoting effect of titanium of Chinese cabbage grown in a hydroponic culture. The added culture solution, either with the specific Ti-bearing solution or the ordinary $TiCl_4$, stimulated cabbage development in terms of plant height, leaf area and chlorophyll content (Zheng *et al*., 2010).

Ti-ascorbate and $TiCl_4$ caused an increase in the yield of red pepper grown in fields and a greenhouse and this enhancement was higher when titanium was applied as a foliar spray (Martínez-Sánchez *et al*., 1991). It was found that water-soluble and pH-stable chelate forms of titanium such as ascorbate, citrate and malate have a beneficial effect on various physiological processes, i.e. an increase in iron and magnesium contents in plants tissues and chlorophyll a and chlorophyll b biosynthesis, increased nitrate reductase activity and has effects on other enzymatic activities (Pais *et al*., 1991; Hrubý *et al*., 2002). Kužel *et al*. (2003) recorded an increase in magnesium, iron and total chlorophyll content in oats after the application of Ti(IV)-citrate. The effect of titanium was considerably weaker when applied on leaves rather than being added to the nutrient solution. Differences between two different soil types they used (Chermozem and Cambisol) only related to the strength of the effect of titanium; the trends remained in the same direction. According to Kužel *et al*. (2007), titanium is more efficient on Fluvisol than on Chernozem and Luvisol. Other authors (Carvajal *et al*., 1994) have shown that the application of Ti-ascorbate via roots or leaves promoted biomass production and chlorophyll a, chlorophyll b and total chlorophyll content in red pepper grown in a greenhouse. A greater increase in the levels of photosynthetic pigments was observed when titanium was supplied via leaves (although it was not significant for chlorophyll b). Titanium supplementation through Ti-ascorbate can encourage carbohydrate production and plant growth (Carvajal and Alcaraz, 1998).

Titanium has significant biological effects on plants, being beneficial at low concentrations and toxic at higher concentrations (Kužel *et al*., 2003). The optimal doses and dates of titanium application in many crops have not yet been determined. A study carried out in China showed that the triple application of a foliar titanium-containing fertilizer with the trade name Fengtaibao (at the seedling stage, squaring stage, and flowering stage) promoted potato growth. The leaves were dark green, lustrous and thick, and plants were vigorous after the application of titanium-containing fertilizer. The leaves kept green for more than 10 days longer than the control plants (Tan and Wang, 2011).

The aim of this study was to determine the effect of dose and date of foliar application of the plant growth stimulant Tytanit® (Ti-ascorbate) on the assimilation leaf area and chlorophyll content of very early-maturing potato cultivars.

MATERIAL AND METHODS

Experimental site and season

The field experiment was carried out in east-central Poland, at the Agricultural Experimental Station of Siedlce University of Natural Sciences and Humanities (52°03' N; 22°33' E) during three growing seasons 2009, 2010 and 2012, on lessive soil (Luvisol) with a high-to-very high content of available phosphorus (88-128 $mg \cdot kg^{-1}$), a medium-to--very high content of potassium (104-208 $mg \cdot kg^{-1}$)

and a low-to-medium content of magnesium (22-45 mg·kg^{-1}), with acid to slightly acid reaction (pH in 1 mol dm^{-3} KCl from 4.7 to 6.7). The forecrop for potato was spring triticale. Farmyard manure was applied in autumn, at the rate of 30 t·ha^{-1}, and mineral fertilizers were applied at the rates of 80 kg N (ammonium nitrate), 35 kg P (superphosphate) and 100 kg K (potassium sulphate) per hectare in the spring tillage.

Plant material and experimental design

In this experiment, the titanium (Ti) source was the mineral growth stimulant Tytanit® produced by the company Intermag Ltd. Tytanit® contains 8.5 g Ti per 1 dm^3 (0.8% m/m), in the form of Ti-ascorbate. The effect of dose (0.2 dm^3·ha^{-1} and 0.4 dm^3·ha^{-1}) and date of Tytanit® application (the leaf development stage – BBCH 14-16, tuber formation stage – BBCH 41-43, and both the leaf development stage and tuber formation stage – BBCH 14-16 and BBCH 41-43) on the assimilation leaf area and chlorophyll content of very early-maturing potato cultivars Lord and Miłek was investigated. The field experiment was established as a split-block-split-plot design with a control object without Tytanit® with three replications. In successive years, 6-week pre-sprouted seed potatoes were planted on the 15th, 13th and 12th April, 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. Potato cultivation was carried out according to the rules of agronomical practice. After 60 days from planting (BBCH 48), the assimilation leaf area, leaf area index (LAI), specific leaf area (SLA) and chlorophyll content were determined. The measurements were made on four successive 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 (Roztropowicz, 1999). Each plant was harvested twice of 10 leaves of medium size, unwithered, undamaged and not at the top. Discs were cut with a 1.5 cm diameter in the centre of the leaf blade on the main vein of the 10 leaves on each occasion. The cut discs were weighed and calculated for the average weight of one disc. The leaf blades were plucked and weighed from each plant and the average weight of leaves per plant was then calculated:

$$\text{Assimilation leaf area} = \frac{\text{weight of leaves per plant}}{\text{average weight of one disc}} \times \text{one disc area } (\pi r^2)$$

SLA was defined as the ratio of assimilation leaf area/weight of leaves (Pietkiewicz, 1985). The chlorophyll content was estimated using a portable chlorophyll meter SPAD-502 (Minolta, Osaka, Japan). The leaf greenness index (SPAD) reading provides a good estimate of the chlorophyll content of the leaf blade. SPAD readings are highly correlated ($r = 0.97$) with the analytical measurements of the chlorophyll content (Vos and Bom, 1993). The measurements were made on the youngest fully expanded leaf (i.e. the fourth or fifth leaf from the top). The relationship between the tuber weight and the assimilation leaf area and chlorophyll content were also determined.

Statistical analysis

The results of the experiment were analyzed statistically by means of analysis of variance (ANOVA) for the split-block-split-plot design. The analysis of the results was conducted using the orthogonal contrast to compare the control object without Tytanit® with the remaining objects. The significance of differences was determined by the Tukey's test at $P = 0.05$.

Weather conditions

Over the three years of the study, the most favourable thermal and moisture conditions for the early crop potato culture were in the warm and moderately wet growing season of 2012 (Table 1). The year 2009 was very cool and it received the highest amount of precipitation. The low air temperature and heavy rainfall after emergence retarded plant growth. In 2010, the growth and development of plants was hampered by a heavy rainfall in May and drought in the first decade of June. The total precipitation in May was almost two times higher than the long-term mean.

Table 1. Mean air temperatures and precipitation totals during the potato growing season

Year	Months and ten day periods								
	April			May			June		
	I	II	III	I	II	III	I	II	III
Mean air temperature, °C									
2009	9.9	8.7	12.4	12.3	12.3	14.0	13.9	14.3	19.0
2010	7.8	9.7	9.2	12.7	14.8	14.6	18.6	16.7	16.9
2012	3.0	8.9	14.9	15.1	12.2	16.4	13.9	17.6	17.5
Precipitation total, mm									
2009	2.8	5.3	0.0	4.8	14.5	49.6	35.6	43.4	66.2
2010	5.9	2.4	2.4	30.3	41.2	21.7	12.5	47.3	2.8
2012	4.6	21.1	4.2	17.3	33.0	3.1	26.4	37.7	12.1
Sielianin's hydrothermal coefficient									
2009	0.3	0.6	0.0	0.4	1.2	3.5	2.6	3.0	3.5
2010	0.7	0.2	0.3	2.4	2.8	1.5	0.7	2.8	0.2
2012	1.5	2.4	0.3	1.1	2.7	0.2	1.9	2.1	0.7

Hydrothermal coefficient value: up to 0.5 strong drought, 0.51-0.69 drought, 0.70-0.99 mild drought, ≥1 no drought

RESULTS

Assimilation leaf area and leaf area index (LAI)

Tytanit® had a significant effect on the assimilation leaf area. On average over the three years of the study, the assimilation leaf area was higher by 0.0718 m^2 (11.5%) and the leaf area index (LAI) was higher by 0.42 compared with the control object without the growth stimulant (Table 2). Tytanit® had a greater effect on the assimilation leaf area under thermal and moisture conditions less favourable to early crop potato cultivation in the years 2009 and 2010 than in the warmer and moderately moist growing season of 2012.

The Tytanit® dose had a significant effect on the assimilation leaf area in the years unfavourable to the cultivation of potato as an early crop (Table 3). In the cold and very moist growing season of 2009, after the application of 0.4 $dm^3 \cdot ha^{-1}$ of Tytanit® the assimilation leaf area was higher by 0.1024 m^2 (19%) and the LAI by 0.61 as compared with the values at the dose of 0.2 $dm^3 \cdot ha^{-1}$. In the warmer growing season of 2010 with deficient rainfall at the beginning of June, the highest increase in the assimilation leaf area resulted from the lower dose of the growth stimulant. Following the application of 0.2 $dm^3 \cdot ha^{-1}$ of Tytanit®, the assimilation leaf area was higher on average by 0.0753 m^2 (12%) and the LAI by 0.44 as compared with the values at the dose of 0.4 $dm^3 \cdot ha^{-1}$. In the warm and moderately moist growing season of 2012, the differences were smaller and were not statistically significant. In the present study, the dose of Tytanit® and cultivar interaction effect on the assimilation leaf area was not statistically confirmed.

The date of Tytanit® application had a significant effect on the assimilation leaf area (Table 4). With a single application of the growth stimulant, the assimilation leaf area did not differ significantly irrespective of whether it was applied at the leaf development stage (BBCH 14-16) or at the tuber formation stage (BBCH 41-43). With two Tytanit® application, at the leaf development stage and with a repeated treatment at the tuber formation stage (BBCH 14-16 + BBCH 41-43), the assimilation leaf area was, on average, lower by 0.0461 m^2 (7%) and the LAI by 0.28 compared with a single treatment performed at one of these stages. The date of Tytanit® application had the greatest effect on the assimilation leaf area under thermal and moisture conditions less favourable for early crop potato cultivation in the years 2009 and 2010. In the cold and very moist growing season of 2009, the assimilation leaf area was highest with a single application of the growth stimulant in the leaf development stage (BBCH 14-16) – on average

0.6268 m^2, however, in the 2010 with the highest air temperature and, at the same time, the lowest rainfall in the first ten-day period of June, the assimilation leaf area was highest with a single application of Tytanit® in the tuber formation stage (BBCH 41-43) – on average 0.7611 m^2. The LAI value amounted to 3.72 and 4.51, respectively. The study demonstrated the significant effect of the interaction of the years, cultivar and the date of Tytanit® application on the assimilation leaf area (Fig. 1). Under the thermal and moisture conditions in 2009 and 2010, the date of growth stimulant application had a greater effect on the assimilation leaf area and LAI for the Miłek cultivar than for the Lord cultivar.

Table 2. Effect of Tytanit® on assimilation leaf area and chlorophyll content

Treatment	Year			Mean
	2009	2010	2012	
Assimilation leaf area, m^2				
Without Tytanit®	0.4937 a	0.5753 a	0.8102 a	0.6246 a
With Tytanit®	0.5852 b	0.6903 b	0.8139 a	0.6964 b
Leaf area index, m^2·m^{-2}				
Without Tytanit®	2.93 a	3.41 a	4.80 a	3.71 a
With Tytanit®	3.46 b	4.09 b	4.82 a	4.13 b
Specific leaf area, m^2·kg^{-1}				
Without Tytanit®	3.188 a	3.117 a	3.178 a	3.161 a
With Tytanit®	3.174 a	3.435 b	3.261 a	3.290 b
Chlorophyll content (SPAD)				
Without Tytanit®	35.42 a	34.07 a	40.52 a	36.67 a
With Tytanit®	35.76 a	35.79 b	41.61 a	37.72 a

Means followed by the same letters do not differ significantly at P = 0.05

Table 3. Effect of Tytanit® on assimilation leaf area and chlorophyll content

Tytanit® dose	Year			Mean
	2009	2010	2012	
Assimilation leaf area, m^2				
0.2 dm^3·ha^{-1}	0.5339 a	0.7279 a	0.8183 a	0.6934 a
0.4 dm^3·ha^{-1}	0.6364 b	0.6526 b	0.8095 a	0.6995 a
Leaf area index, m^2·m^{-2}				
0.2 dm^3·ha^{-1}	3.17 a	4.31 a	4.76 a	4.20 a
0.4 dm^3·ha^{-1}	3.77 b	3.87 b	4.80 a	4.14 a
Specific leaf area, m^2·kg^{-1}				
0.2 dm^3·ha^{-1}	3.142 a	3.468 a	3.212 a	3.274 a
0.4 dm^3·ha^{-1}	3.206 a	3.401 a	3.311 a	3.306 a
Chlorophyll content (SPAD)				
0.2 dm^3·ha^{-1}	35.81 a	35.88 a	41.41 a	37.70 a
0.4 dm^3·ha^{-1}	35.70 a	35.71 a	41.81 a	37.74 a

Means followed by the same letters do not differ significantly at P = 0.05

Table 4. Effect of date of Tytanit® application on assimilation leaf area and chlorophyll content

Date of Tytanit® application	Year			Mean
	2009	2010	2012	
Assimilation leaf area, m^2				
BBCH 14-16	0.6268 a	0.6854 a	0.7954 a	0.7025 a
BBCH 41-43	0.5776 ab	0.7611 b	0.8245 a	0.7211 a
BBCH 14-16 + BBCH 41-43	0.5511 b	0.6243 c	0.8218 a	0.6657 b
Leaf area index, $m^2 \cdot m^{-2}$				
BBCH 14-16	3.72 a	4.06 a	4.71 a	4.16 a
BBCH 41-43	3.42 ab	4.51 b	4.89 a	4.28 a
BBCH 14-16 + BBCH 41-43	3.26 b	3.70 c	4.87 a	3.94 b
Specific leaf area, $m^2 \cdot kg^{-1}$				
BBCH 14-16	3.165 a	3.418 a	3.226 a	3.270 a
BBCH 41-43	3.214 a	3.590 b	3.291 a	3.365 b
BBCH 14-16 + BBCH 41-43	3.142 a	3.295 c	3.266 a	3.235 a
Chlorophyll content (SPAD)				
BBCH 14-16	35.86 a	35.74 a	41.62 a	37.74 a
BBCH 41-43	36.04 a	35.98 a	41.42 a	37.81 a
BBCH 14-16 + BBCH 41-43	35.36 a	35.65 a	41.78 a	37.60 a

Means followed by the same letters do not differ significantly at P = 0.05

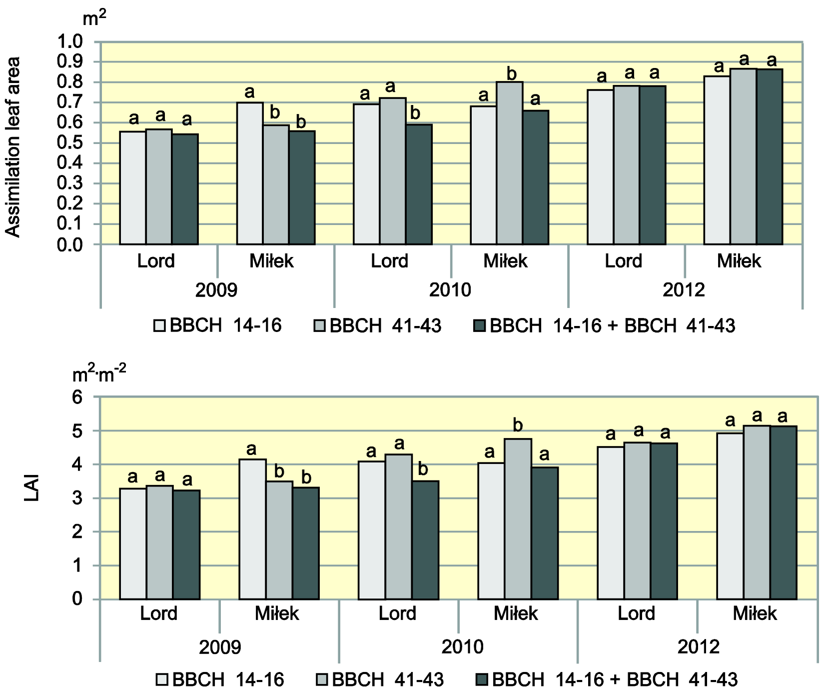

Fig. 1. Assimilation leaf area and leaf area index (LAI) in relation to the date of Tytanit® application, cultivar and potato growing season; means followed by the same letters do not differ significantly at P = 0.05

Specific leaf area (SLA)

Tytanit® had a significant effect on the specific leaf area (Table 2). With the Tytanit® application the SLA was higher, on average, in the three years of the study by 0.129 $m^2 \cdot kg^{-1}$ compared with the control object without the growth stimulant. Tytanit® had the greatest effect on the SLA in 2010, which was the year with the highest air temperature and the lowest rainfall in the first decade of June.

The Tytanit® dose and cultivar interaction effect on SLA was statistically confirmed. The Tytanit® dose had a significant effect on the SLA for the Lord cultivar only (Fig. 2). The SLA was higher following the application of 0.4 $dm^3 \cdot ha^{-1}$ of Tytanit®.

The SLA depended to a great extent on the date of Tytanit® application (Table 4). The SLA was the highest when the growth stimulant was only applied in the tuber formation stage (BBCH 41-43). The date of Tytanit® application had the greatest effect on the SLA in 2010 with the highest air temperature and, at the same time, the lowest rainfall in the ten-day period of June. The date of Tytanit® application and cultivar interaction effect on SLA was not statistically confirmed.

The performed study demonstrated a significant effect of the interaction of the dose and the date of Tytanit® application on the SLA (Fig. 3). The treatment date had a greater effect on the SLA when Tytanit® was applied at a dose of 0.2 $dm^3 \cdot ha^{-1}$, particularly under the thermal and moisture conditions of 2009 and 2010 that were less favourable to early crop potato cultivation.

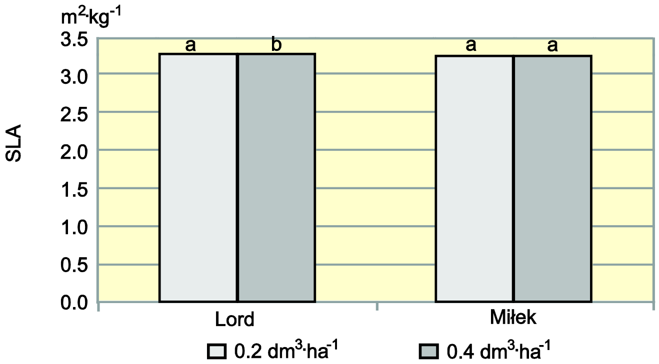

Fig. 2. Specific leaf area (SLA) in relation to the Tytanit® dose and cultivar; means followed by the same letters do not differ significantly at P = 0.05

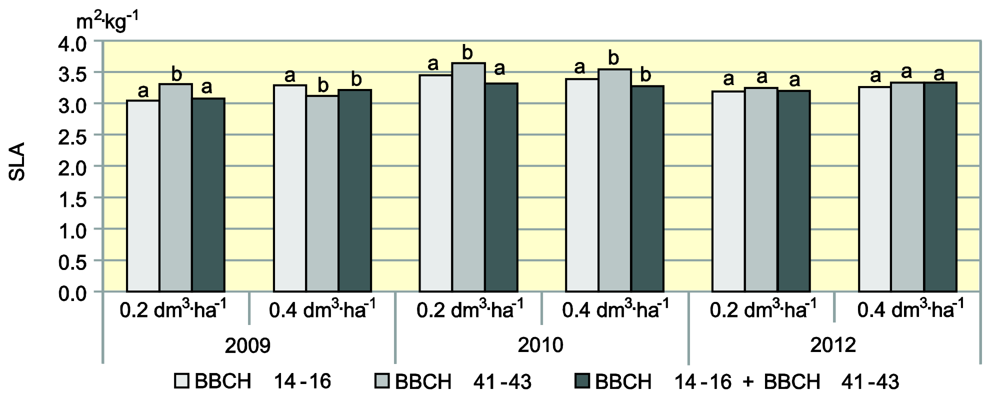

Fig. 3. Specific leaf area (SLA) in relation to the dose and date of Tytanit® application and potato growing season; means followed by the same letters do not differ significantly at P = 0.05

Chlorophyll content (SPAD)

Tytanit® had a significant effect on the chlorophyll content in leaves only in 2010, a year with the highest air temperature and the lowest rainfall in the first decade of June (Table 2). In that year, with the Tytanit® application, the leaf greenness index (SPAD) was on average higher by 1.72 than the control object without the growth stimulant.

The dose and date of Tytanit® application had no significant effect on the chlorophyll content (Tables 3 and 4). The SPAD value depended to a greater extent on the potato cultivar and the weather conditions during the potato growing season.

Relationship between tuber weight and assimilation leaf area and chlorophyll content

Tytanit® had a significant effect on the tuber weight per plant according to the work by Kalinowski and Wadas (2017). In their study, Tytanit® caused an increase in the tuber weight per plant and a smaller tuber weight variability over the various years. The potato cultivars showed a differential response to Tytanit®. The growth stimulant had a greater effect on the tuber weight per plant for the Lord cultivar. Tytanit® dose slightly affected the tuber weight per plant for both cultivars. The tuber weight depended to a greater extent on the date of Tytanit® application. With a single application of the growth stimulant the tuber weight per plant did not differ significantly irrespective of whether the application was at the leaf development stage (BBCH 14-16) or at the tuber formation stage (BBCH 41-43). With a double Tytanit® application (at the leaf development stage and with a repeated treatment at the tuber formation stage) the tuber weight per plant was lower than after a single application.

The tuber weight per plant was not significantly correlated with assimilation leaf area and LAI. No significant correlation was found between the tuber weight and SLA (Table 5). A significant and negative correlation was found between the tuber weight per plant and chlorophyll content (SPAD) only for the Lord cultivar and it was for both cultivation with and without Tytanit®.

Table 5. Correlation coefficient between the tuber weight and assimilation leaf area and chlorophyll content

Plant growth characteristics	Cultivar and treatment			
	Lord		Miłek	
	without Tytanit®	with Tytanit®	without Tytanit®	with Tytanit®
Assimilation leaf area	-0.4631	-0.4803	0.1294	0.3110
LAI	-0.4618	-0.4809	0.1294	0.3115
SLA	0.4844	0.2533	0.1233	0.0286
SPAD	-0.8258*	-0.8946*	0.2839	0.2716

* Significant at P = 0.05

DISCUSSION

The duration of active leaf growth mainly determines potato yield and is a major limiting factor with early-maturing cultivars (Lahlou *et al*., 2003; Geremew *et al*., 2007). The assimilation leaf area and the type of foliage form the architecture of lowland fields and largely determines the effectiveness of solar radiation interception (Zrůst *et al*., 1999). The rate of leaf area expansion has been shown to have an interaction between genotype and environment, and varied by year (van Delden *et al*., 2000; Boyd *et al*., 2002). In modern agriculture, plant growth stimulants have been gaining increasing importance. Growth stimulants increase plant resistance to abiotic stresses, which allows better use of the cultivar production potential under the environmental conditions in the area of cultivation. Titanium exhibits the properties of a biostimulant. It exerts a beneficial effect on various physiological processes of plants, leading to earlier and higher crop production (Du *et al*., 2010). Titanium stimulates plant growth in a species--specific manner (Pais, 1983; Dumon and Ernst, 1988; Du *et al*., 2010). A study carried out in China showed the growth-promoting effect of titanium on potato (Tan and Wang, 2011), and this has been confirmed in the present study. Tytanit® caused an enlargement of the assimilation leaf area. Studies by other authors have demonstrated the favourable effect of Tytanit® on the assimilation leaf area of small--sized tomatoes (Dobromilska, 2007) and Chinese cabbage (Zheng *et al*., 2010). In our study, the effect of Tytanit® on the assimilation leaf area depended on the dose of plant growth stimulant and weather conditions. Under thermal and moisture conditions unfavourable for early crop potato cultivation, a greater enlargement of the assimilation leaf area resulted from a dose of 0.4 $dm^3 \cdot ha^{-1}$, while in the warmer growing season with deficient rainfall at the beginning of June a Tytanit® dose of 0.2 $dm^3 \cdot ha^{-1}$ stimulated the production of leaves more strongly than a dose of 0.4 $dm^3 \cdot ha^{-1}$. It has been reported that a Tytanit® dose of 0.4 $dm^3 \cdot ha^{-1}$ stimulated the production of rape biomass more strongly than a dose of 0.2 $dm^3 \cdot ha^{-1}$ (Kováčik *et al*., 2014). According to Hrubý *et al*. (2002) and Kužel *et al*. (2003) titanium exerts a favourable effect on plant growth only at low concentrations, while at higher concentrations it may exhibit toxic effects. Whether the titanium amount exerts a stimulating or a toxic effect depends, *inter alia*, on the plant species and age (Dumon and Ernst, 1988). It is very important to determine the optimal doses and dates of titanium application in order to optimise early potato production. In the present study, the plants produced a greater assimilation leaf area when Tytanit® was only applied once, in the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). With two Tytanit® applications (i.e. in the initial plant growth period and with a repeated treatment in the tuber formation stage), the assimilation leaf area was lower. However, a study carried out in China demonstrated that the triple application of foliar titanium-containing fertilizer (at the seedling stage, squaring stage, and flowering stage) promoted potato growth (Tan and Wang, 2011).

The leaf area index (LAI) is one of the physiological parameters indicating the performance of crop growth and partitioning of assimilates. A higher LAI value favourably affected the tuber growth during vegetation and even the final tuber yield (Zrůst *et al*., 1999). According to Li *et al*. (2013) and Darabad *et al*. (2014), leaf area index had a significant positive correlation with tuber yield. This suggests that the enlargement of leaf area could enhance the export of photosynthetic product and cause an increase in economic yield. In the three years of the study, after Tytanit® application the LAI averaged 4.13 and was higher by 0.42 when compared with the cultivation without the plant growth stimulant. Studies have shown a rapid increase in light interception together with an increase in LAI of up to 2.5 (Firman and Allen, 1989). The light interception rises, though slowly, until LAI reaches 4.0 (Boyd *et al*., 2002). According to de la Casa *et al*. (2011), if in potato the LAI exceeds 3.0, the intercepted photosynthetically active radiation values change very little, making it very difficult to detect differences due to variations in crop conditions. Camargo *et al*. (2016) showed that the highest light absorption efficiency values occurred at the LAI value of 3, which corresponded to maximum ground cover. In the present study, the LAI value was higher than 3.0, which is presumed to be the optimum (Rykaczewska, 2004; de la Casa *et al*., 2011; Camargo *et al*., 2016), and yet a correlation between the tuber weight and LAI was not found. The relationship between the rate of tuber yield and the 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. It often happens that the enlargement of assimilation leaf area does not result in an increase in the tuber yield (Zrůst *et al*., 1999). The LAI value is determined by light conditions in lowland fields of crops and the effectiveness of solar radiation interception. The rate of photosynthesis per unit of leaf area decreases with the increase in leaf area (Pietkiewicz, 1985; Zrůst *et al*., 1999; Zarzyńska, 2001).

The leaf area index (LAI) describes the growth in lowland fields, whereas the growth of individual plants is characterized with the specific leaf area (SLA). The SLA for potato depends on the growth stage and temperature. The early foliar expansion is associated with a strong increase in SLA (van Delden *et al*., 2000). With a Tytanit® application the SLA was higher than it was in the cultivation without the growth stimulant, particularly under stress conditions. The Tytanit® dose (0.2 or 0.4 $dm^3 \cdot ha^{-1}$) had a significant effect on the SLA for the Lord cultivar only. The SLA of this cultivar was higher following the application of 0.4 $dm^3 \cdot ha^{-1}$ of Tytanit®. The SLA depended to a great extent on the date of plant growth stimulant application. The SLA was the highest when Tytanit® was only applied once in the tuber formation stage (BBCH 41-43). The higher SLA with the similar LAI indicates that with the Tytanit® application in the tuber formation stage (BBCH 41-43) the leaves were thinner and more delicate than following growth stimulant application in the initial stage of plant growth (BBCH 14-16). A correlation between the tuber weight per plant and SLA was not found. According to Ascione *et al*. (2013), the tuber growth rate is only slightly correlated with LAI, and still less so with SLA, which was confirmed in the present study.A study carried out in China showed that after a triple application of foliar titanium-containing fertilizer potato leaves were dark green, lustrous and thick (Tan and Wang, 2011), which was confirmed in the present study after application of Tytanit®. Following the Tytanit® application, the leaf greenness index (SPAD) was, under stress conditions, higher compared with the cultivation without plant growth stimulant. Studies of other authors have demonstrated that Tytanit® application promoted chlorophyll content in the leaves of timothy-grass (Radkowski, 2013) and winter wheat and winter rape (Kováčik *et al*., 2014). In the present study, the dose and date of Tytanit® application slightly affected the chlorophyll content in leaves of very early-maturing potato cultivars. Kováčik *et al*. (2014) showed the positive effect of a double spraying of Mg-Tytanit on the chlorophyll content in the leaves of winter wheat and winter rape. The chlorophyll content was higher in the plants fertilized by a Mg-Tytanit dose of 0.2 $dm^3 \cdot ha^{-1}$ than in those fertilized by a dose of 0.4 $dm^3 \cdot ha^{-1}$ for each spraying. A third spraying of both application doses of Mg-Tytanit tended to decrease the chlorophyll content in both crops. The present study showed a significant and negative correlation between the tuber weight and chlorophyll content in leaves (SPAD value) for the Lord cultivar. This correlation was not found for the Miłek cultivar. Bărăscu *et al*. (2016) found a significant and positive correlation between SPAD and aboveground plant weight, and a significant and negative correlation between SPAD and the tuber weight. The negative correlation between SPAD and tuber weight could be associated with an oxidative stress (Ramírez *et al*., 2014).

CONCLUSIONS

Leaf area determines the effectiveness of solar radiation interception and potato tuber yield and the rate of leaf area expansion depends on genotype and environment. Growth stimulants increase plant resistance to abiotic stresses, which allows better use of the potato cultivar production potential under the environmental conditions of the area of cultivation. The present study demonstrated the stimulating effects of titanium ions (Tytanit®) on the assimilation leaf area and chlorophyll content of very early-maturing potato cultivars. Following the Tytanit® application, the plants produced a greater assimilation leaf area, particularly under stress conditions. Under thermal and moisture conditions unfavourable for the growth of very early-maturing potato cultivars (a cold and very moist growing season), a Tytanit® dose of 0.4 $dm^3 \cdot ha^{-1}$ stimulated the growth of leaves more strongly than a dose of 0.2 $dm^3 \cdot ha^{-1}$. The plants produced a greater assimilation leaf area when Tytanit® was only applied once irrespective of whether it was at the leaf development stage (BBCH 14-16) or at the tuber formation stage (BBCH 41-43). A double Tytanit® application, i.e. the first application in the initial plant growth stage (BBCH 14-16) and a repeated treatment in the tuber formation stage (BBCH 41-43), resulted in a reduction in assimilation leaf area compared with a single treatment performed either in the initial stage of plant growth or in the tuber formation stage. Following Tytanit® application, the leaf area index (LAI), which describes the growth of lowland fields, was on average 4.13 and was higher by 0.42 compared with the cultivation without growth stimulant. The specific leaf area (SLA) characterizing the growth of individual plants averaged 3.290 $m^2 \cdot kg^{-1}$ and was higher by 0.129 $m^2 \cdot kg^{-1}$ than in the cultivation without growth stimulant. The SLA was the highest when Tytanit® was applied only once in the tuber formation stage (BBCH 41-43). Tytanit® stimulated chlorophyll biosynthesis in leaves. The dose and date of Tytanit® application slightly affected the leaf greenness index (SPAD).

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WPŁYW TYTANU NA POWIERZCHNIĘ ASYMILACYJNĄ LIŚCI I ZAWARTOŚĆ CHLOROFILU BARDZO WCZESNYCH ODMIAN ZIEMNIAKA

Streszczenie

Tytan podany dokorzeniowo lub dolistnie stymuluje wzrost roślin w sposób specyficzny dla gatunku. Ma korzystny wpływ na wzrost roślin tylko w małym stężeniu, natomiast w wyższych stężeniach może wykazywać działanie toksyczne. Badano wpływ dawki (0,2 $dm^3 \cdot ha^{-1}$ i 0,4 $dm^3 \cdot ha^{-1}$) i terminu (faza rozwoju liści – BBCH 14-16, faza zawiązywania bulw – BBCH 41-43, faza rozwoju liści i faza zawiązywania bulw) stosowania Tytanitu® (8,5 g Ti w 1 dm^3) na powierzchnię asymilacyjną liści i zawartość chlorofilu bardzo wczesnych odmian ziemniaka. Tytanit® powodował zwiększenie powierzchni asymilacyjnej liści i zawartości chlorofilu w liściach, szczególnie w warunkach stresowych. W warunkach termicznych i wilgotnościowych, niekorzystnych do wzrostu bardzo wczesnych odmian ziemniaka, dawka Tytanitu® 0,4 $dm^3 \cdot ha^{-1}$ stymulowała wzrost liści bardziej niż 0,2 $dm^3 \cdot ha^{-1}$. Powierzchnia asymilacyjna liści była większa, gdy Tytanit® był stosowany tylko raz, w fazie rozwoju liści (BBCH 14-16) lub w fazie zawiązywania bulw (BBCH 41-43). Po zastosowaniu Tytanitu® wskaźnik pokrycia liściowego (LAI) wynosił średnio 4,13 i był większy o 0,42 w porównaniu z uprawą bez stymulatora wzrostu, natomiast ciężar jednostki powierzchni liści (SLA) wynosił 3,290 $m^2 \cdot kg^{-1}$ i był większy o 0,129 $m^2 \cdot kg^{-1}$ niż w uprawie bez stymulatora wzrostu. SLA był największy, gdy Tytanit® był stosowany tylko w fazie zawiązywania bulw (BBCH 41-43). Tytanit® stymulował biosyntezę chlorofilu w liściach. Dawka i termin stosowania Tytanitu® miały niewielki wpływ na wskaźnik zieloności liści (SPAD).

Słowa kluczowe: ciężar jednostki powierzchni liści (SLA), powierzchnia asymilacyjna liści, Tytanit®, wskaźnik pokrycia liściowego (LAI), wskaźnik zieloności liści (SPAD)