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EFFECT OF TITANIUM ON GROWTH OF VERY EARLY-MATURING POTATO CULTIVARS

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ABSTRACT

A condition for achieving a high potato tuber yield on an early harvest is to provide plants with good growth conditions. In modern horticulture, plant growth stimulants have been gaining increasing importance. This study examined the effect of dose (0.2 dm^3 ha^{-1} or 0.4 dm^3 ha^{-1}) and date (leaf development stage – BBCH 14-16, tuber formation stage – BBCH 41-43, leaf development stage and tuber formation stage) of Tytanit® application (8.5 g Ti in 1 dm^3) on the growth of very early-maturing potato cultivars ('Lord', 'Miłek'). Following the Tytanit® application, the plants were higher and produced a greater above-ground biomass and tuber weight, however, the leaf weight ratio (LWR) and leaf area ratio (LAR) were lower than in the cultivation without the growth stimulant. Tytanit® had a greater effect on the leaf weight ratio (LAR) and tuber weight for the 'Lord' cultivar. Tytanit® dose had no effect on the plant growth. A double Tytanit® application resulted in a reduction in the length and weight of stems and tuber weight. The date of Tytanit® application had no effect on the weight of leaves. The leaf area ratio (LAR) was the highest when Tytanit® was only applied in the tuber formation stage, and the leaf weight ratio (LWR) was the highest when Tytanit® was applied twice. A positive correlation was found between the tuber weight and the LWR and LAR.

Key words: plant height, above-ground biomass, leaf area ratio (LAR), leaf weight ratio (LWR), tuber weight, Tytanit®

INTRODUCTION

Titanium (Ti) is the tenth most common element in the Earth's crust. It is present in soil in a range from several tenths of a percent up to several percentage points. The overwhelming majority of titanium is poorly available for plants, because it is present mostly in the form of minerals (as TiO_2 or $FeTiO_3$) that are insoluble in water. Titanium is classified as a beneficial element for plants, which can promote or improve the growth and development of some plant species or under specific growth conditions [Pais 1983, Dumon and Ernst 1988, Pais et al. 1991, Carvajal and Alcaraz 1998]. Titanium under ordinary circumstances is not taken up by plants; however, when applied as Ti-chelate organic acids such as ascorbate, citrate and malcate, it has a beneficial effect on various physiological processes. Titanium fertilizer applied via roots or leaves in growth experiments stimulates plant growth in a species-specific manner. It can stimulate chlorophyll content and the activities of enzymes such as catalase, peroxidase, lipoxygenase and nitrogen reductase, and the uptake of major and minor nutrients,

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as well as accelerate plant growth, increase crop yield and improve the crop quality [Pais 1983, Dumon and Ernst 1988, Carvajal and Alcaraz 1998, Hrubý et al. 2002, Grenda 2003, Du et al. 2010]. Although titanium stimulates the plants at low doses, it is phytotoxic (chlorosis, necrosis, growth inhibition) at higher ones. The amount of titanium which plants require for growth stimulation cannot be defined as an absolute norm. The critical concentration for beneficial or toxic effects of titanium depends on the plant species, plant age, and the tissue concentration of other minerals [Dumon and Ernst 1988]. The foliar application of titanium caused significant toxic manifestations on tabacco [Maroti et al. 1984] and oats [Hrubý et al. 2002, Kužel et al. 2007]. Magnesium partially ameliorates these toxic effects if applied together with titanium [Kužel et al. 2007]. Many positive beneficial effects, as well as a few adverse effects of titanium application are described in the literature. Titanium foliar applications or as a nutrient solution additive affected plant height and stimulated the formation of aboveground and underground phytomass of oat [Hrubý et al. 2002, Kužel et al. 2003], small-sized tomato [Dobromilska 2007], Chinese cabbage [Zheng et al. 2010], potato [Tan and Wang 2011], winter rape [Kováčik et al. 2014] and annual bedding plants [Whitted-Haag et al. 2014]. The application of titanium dioxide (TiO_2) can promote the growth of strawberry plants suffering from a shortage of sunlight in a greenhouse during the winter season [Choi et al. 2015]. According to other authors, titanium application did not affect tomato growth in a reenhouse [Borkowski et al. 2000] or the root volume and fresh and dry weight of tomato shoots grown in a hydroponic culture [Haghighi and Daneshmand 2013]. It was found that titanium effect on plant growth depended of the nitrogen form in the nutrient solution. Titanium was beneficial for plants grown on the nitrate-containing nutrient solutions, whereas on the ammonium-containing nutrient solutions, titanium results in an inhibitory effect on plant growth (decrease in top height and root length, top and root dry weight, and chlorophyll contents). Therefore, it was conclued that an increase in nitrate reductase activity was mainly responsible for the titanium beneficial effect on plants [Hrubý et al. 2002]. The effect of foliar titanium applications was substantially influenced by the nutrient nitrogen status of the individual plants. The plant response to titanium application was almost negligible under nitrogen deficiency. In nitrogen-treated plots, the response were much clearer but not many significant differences were found, confirming the high soil buffering capacity and many counteracting effects under field conditions [Tlustoš et al. 2005]. Nearly all experiments studying the effect of titanium on plant growth were carried out in a hydroponic culture or in greenhouse. To date, few studies have been focused on the effects of titanium on plant growth under field conditions. According to Kužel et al. [2007], titanium is more efficient on Fluvisol than on Chernozem and Luvisol. A study carried out in China showed that the application of foliar titanium-containing fertilizer with the trade name Fengtaibao promoted the growth of potato. Leaves were dark green, lustrous and thick, and plants were vigorous after the foliar application of titanium-containing fertilizer [Tan and Wang 2011].

The aim of the study was to determine the effect of dose and date of foliar application of mineral growth stimulant Tytanit® (Ti-ascorbate) on the growth of very early-maturing potato cultivars.

MATERIALS AND METHODS

Experimental site and season. The field experiment was carried out at the Agricultural Experimental Station of the Siedlce University of Natural Sciences and Humanities, in central-eastern Poland (52°03'N, 22°33'E) during three growing seasons 2009, 2010 and 2012, on loamy soil (Luvisol) with a high-to-very high content of available phosphorus (88–128 mg kg^{-1}), a medium-to-very high content of potassium (104–208 mg kg^{-1}), a low-to-medium content of magnesium (22–45 mg kg^{-1}), a low content of boron (0.29–1.00 mg kg^{-1}), copper (1.3–2.2 mg kg^{-1}) and zinc (4.1–9.3 mg kg^{-1}), a medium content of manganese (65.2–95.3 mg kg^{-1}) as well as a high content of iron (550–730 mg kg^{-1}). The organic carbon content in the soil ranged from 7.89 to 14.21 g kg^{-1} of soil, pH in 1 M KCl from 4.7 to 6.7. In each year of the study, spring triticale was grown as a potato forecrop. Farmyard manure was applied in autumn, at the rate of 30 t ha^{-1}, and mineral fertilizers were applied in rates 80 kg N (ammonium nitrate), 35 kg P (superphosphate) and 100 kg K (potassium sulphate) per hectare in spring.

Plant material and experimental design. In this experiment, the titanium (Ti) source was the mineral growth stimulant Tytanit® produced by INTERMAG Ltd., Olkusz, Poland. Tytanit® contained 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, the leaf development stage and tuber formation stage – BBCH 14-16 and BBCH 41-43) on the growth of very early-maturing potato cultivars 'Lord' and 'Miłek' was investigated. The field experiment was established in a split-block-split-plot design with a control object without Tytanit® in three replication. In successive years, 6-week pre-sprouted seed potatoes were planted on 15, 13 and 12 April , with a row spacing of 25 cm and 67.5 cm between rows. The average length of sprouts at the time of planting amounted to 15–20 mm. The plot area was 15 m^2 (96 plants). Potato cultivation was carried out according to the rules of agronomical practice. After 60 days from planting (BBCH 48), the height of plants, weight of leaves, weight of stems, leaf weight ratio (LWR) and leaf area ratio (LAR) were determined. The measurements were made on four successive plants per plot. LWR and LAR were defined as the ratio of the weight of leaves/weight of the whole plant and the ratio of assimilation leaf area/weight of the whole plant, respectively [Pietkiewicz 1985]. Potatoes were harvested 75 days after planting (the end of June). The tuber weight per plant was determined on ten successive plants per plot.

Table 1. Effect of experimental factors and their interactions on potato plant growth

Factor	Plant height	Weight of leaves	Weight of stems	Leaf weight ratio (LWR)	Leaf area ratio (LAR)	Tuber weight
Year (Y)	**	**	**	**	**	ns
Contrast (T)[1]	*	*	**	**	*	*
Y × T	ns	ns	ns	ns	ns	ns
Cultivar (A)	**	**	**	**	**	**
Y × A	ns	ns	ns	ns	**	**
T × A	ns	ns	ns	ns	**	**
Y × T × A	ns	ns	ns	ns	**	**
Tytanit® dose (B)	ns	ns	ns	ns	ns	ns
Y × B	ns	**	**	ns	ns	ns
A × B	ns	ns	ns	ns	ns	ns
Y × A × B	ns	ns	ns	ns	**	**
Date of Tytanit® application (C)	**	ns	**	**	*	**
Y × C	**	*	**	**	ns	**
A × C	ns	ns	ns	ns	ns	ns
Y × A × C	ns	**	**	ns	ns	*
B × C	ns	ns	ns	**	**	ns
Y × B × C	ns	*	ns	**	**	ns
A × B × C	ns	ns	ns	ns	ns	ns
Y × A × B × C	ns	**	ns	*	**	ns

[1] Contrast – comparison the control object without Tytanit® with the test objects with Tytanit®
* significant at P ≤ 0.05, ** significant at P ≤ 0.01, ns – non-significant

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

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

Statistical analysis. The results of the three-way field experiment with a control object were analysed statistically by means of analysis of variance (ANOVA) for the split-block-split-plot design. The analysis of the results of the study was conducted using the orthogonal contrast to compare the control object without Tytanit® with the test objects with Tytanit®. The significance of differences was verified using Tukey's test at $P \leq 0.05$. Table 1 presents the effect of the experimental factors and their interactions on the examined characteristics of potato plant growth.

Weather conditions. Over the three years of the study, the most favourable thermal and moisture conditions for early crop potato culture were in the warm and moderately wet growing season of 2012 (tab. 2). 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. Total precipitation in May was almost two times higher than the long-term average.

RESULTS

Plant height and above-ground plant biomass. Tytanit® had a significance effect on the plant growth. In the three years of the study, the plants were higher by 3.6 cm, on average, the average weight of leaves was higher by 14 g (7%), and the average weight of stems was higher by 38 g (16%) as compared with the control object without the growth stimulant (tab. 3).

The rate of plant growth was cultivar-dependent (tab. 4). Regardless of the treatment (with or without Tytanit®), the length and weight of stems were higher for the 'Lord' cultivar than for the 'Miłek' cultivar, whereas, 'Miłek' had a higher weight of leaves. The examined early-maturing potato cultivars showed a similar response to Tytanit®.

The Tytanit® dose had no effect on plant height (tab. 4). The effect of the Tytanit® dose on the above-

Table 3. Effect of Tytanit® on potato plant growth

Treatment	Plant height (cm)	Weight of leaves (g)	Weight of stems (g)	Leaf weight ratio (g g^{-1})	Leaf area ratio (cm^2 g^{-1})	Tuber weight (g)
Without Tytanit®	61.4 b	199 b	238 b	0.458 a	14.68 a	584 b
With Tytanit®	65.0 a	213 a	276 a	0.441 b	14.38 b	632 a

Means within columns followed by the same letters do not differ significantly at $P \le 0.05$

Table 4. Effect of experimental factors on potato plant growth

Experimental factors	Plant height (cm)	Weight of leaves (g)	Weight of stems (g)	Leaf weight ratio ($g \cdot g^{-1}$)	Leaf area ratio ($cm^2 \cdot g^{-1}$)	Tuber weight (g)
Cultivar						
Lord	68.1 a	200 b	298 a	0.405 b	13.22 b	597 b
Miłek	60.8 b	222 a	244 b	0.482 a	15.63 a	653 a
Tytanit® dose						
0.2 $dm^3 ha^{-1}$	65.2 a	212 a	274 a	0.441 a	14.40 a	641 a
0.4 $dm^3 ha^{-1}$	64.8 a	214 a	278 a	0.441 a	14.36 a	623 a
Date of Tytanit® application						
BBCH 14-16	66.7 a	217 a	288 a	0.436 b	14.23 b	655 a
BBCH 41-43	64.9 ab	217 a	286 a	0.438 b	14.57 a	640 a
BBCH 14-16 + BBCH 41-43	63.3 b	205 a	254 b	0.450 a	14.35 ab	600 b
Year						
2009	54.4 c	182 c	226 b	0.448 b	14.26 b	635 a
2010	78.4 a	200 b	288 a	0.421 c	14.08 b	622 a
2012	60.5 b	252 a	298 a	0.461 a	14.93 a	617 a

Means within columns followed by the same letters do not differ significantly at $P \le 0.0$

Table 5. Plant height and above-ground plant biomas in relation to the year and Tytanit® dose

Tytanit® dose	Year		
	2009	2010	2012
Plant height (cm)			
0.2 dm^3 ha^{-1}	53.4 a	80.8 a	61.4 a
0.4 dm^3 ha^{-1}	56.4 a	78.0 a	59.9 a
Weight of leaves (g)			
0.2 dm^3 ha^{-1}	171 b	211 a	255 a
0.4 dm^3 ha^{-1}	199 a	194 a	249 a
Weight of stems (g)			
0.2 dm^3 ha^{-1}	208 b	317 a	299 a
0.4 dm^3 ha^{-1}	254 a	276 b	304 a

Means within columns followed by the same letters do not differ significantly at $P \le 0.05$

ground plant biomass depended on weather conditions during the potato growing season (tab. 5). In the cold and very moist growing season of 2009, after the application of 0.4 $dm^3 ha^{-1}$ of Tytanit®, the average weight of leaves was higher by 28 g (16%) and the weight of stems by 46 g (22%) as compared with the dose of 0.2 $dm^3 ha^{-1}$. In the warmer growing season of 2010 with deficient rainfall at the beginning of June, a highest increase in the above-ground plant biomass was a result of a smaller dose of the growth stimulant. Following the application of 0.2 $dm^3 ha^{-1}$ of Tytanit®, the weight of leaves was on average higher by 17 g (9%) and the weight of stems by 41 g (15%). In the warm and moderately moist growing season of 2012, the differences were smaller and were not statistically significant. The cultivar and Tytanit® dose interaction effect on plant height and above-ground plant biomass was not statistically confirmed.

The date of Tytanit® application had a significant effect on the plant height and above-ground plant biomass (tab. 4). Regardless of the Tytanit® dose, with a single application of the growth stimulant, the plant height and above-ground plant biomass did not differ significantly in either the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). With two Tytanit® applications, in the leaf development stage and with a repeated tre-

Table 6. Plant height, above-ground plant biomas and tuber weight in relation to the year and date of Tytanit® application

Date of Tytanit® application	Year		
	2009	2010	2012
Plant height (cm)			
BBCH 14-16	57.4 a	82.0 a	60.7 a
BBCH 41-43	53.6 a	80.8 a	60.4 a
BBCH 14-16 + BBCH 41-43	53.7 a	75.3 b	61.0 a
Weight of leaves (g)			
BBCH 14-16	200 a	205 ab	248 a
BBCH 41-43	179 b	218 a	254 a
BBCH 14-16 + BBCH 41-43	175 b	186 b	254 a
Weight of stems (g)			
BBCH 14-16	252 a	310 a	304 a
BBCH 41-43	226 a	330 a	302 a
BBCH 14-16 + BBCH 41-43	214 a	248 b	300 a
Leaf weight ratio ($g g^{-1}$)			
BBCH 14-16	0.442 a	0.411 b	0.454 a
BBCH 41-43	0.448 a	0.398 b	0.467 a
BBCH 14-16 + BBCH 41-43	0.453 a	0.438 a	0.456 a
Tuber weight (g)			
BBCH 14-16	659 a	670 a	635 a
BBCH 41-43	650 a	652 a	618 a
BBCH 14-16 + BBCH 41-43	593 b	572 b	636 a

Means within columns followed by the same letters do not differ significantly at $P \leq 0.05$

atment in the tuber formation stage (BBCH 14-16 + BBCH 41-43), the plants were, on average, lower by 2.5 cm and the average weight of stems was smaller by 34 g (13%) compared with a single treatment performed on each of these dates. The difference in the weight of leaves was smaller and was not statistically confirmed. The date of Tytanit® application had the greatest effect on the plant height and above-ground plant biomass in the 2010 with the highest air temperature and, at the same time, the lowest rainfall in the first ten-day period of June (tab. 6). In that year, with two Tytanit® applications, the plants were lower, on average, by 6.1 cm, and the weight of leaves was, on average, lower by 25 g (13%) and the weight of stems was lower by 72 g (29%) than with a single treatment, in the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). The cultivar and date of Tytanit® application interaction effect on plant height and above-ground plant biomass was not statistically confirmed. The study demonstrated a significant effect of the interaction of the year, cultivar and the date of Tytanit® application on the above-ground plant biomass (tab. 7). Under thermal and moisture conditions in 2009 and 2010, the date of growth stimulant application had a greater effect on the above-ground plant biomass of 'Miłek' cultivar than for plants of the 'Lord' cultivar. In the coldest and very moist growing season of 2009, the above-ground plant biomass of 'Miłek' cultivar was highest with a single application of the growth stimulant in the leaf development stage (BBCH 14-16), however, in the 2010 with the higher air temperature, at the same time, the lowest rainfall in the first ten-day period of June, the above-ground plant biomass of 'Miłek' was highest with a single application of Tytanit® in the tuber formation stage (BBCH 41-43).

The dose and date of Tytanit® application interaction effect on length and weight of stems was not statistically confirmed. The performed study demonstrated a significant effect of the interaction of the years with the dose and date of Tytanit® application on the weight of leaves (tab. 8). In the coldest and very moist growing season of 2009, the plants produced the greatest weight of leaves when Tytanit® was applied at a dose of 0.2 $dm^3 ha^{-1}$ in the leaf development stage (BBCH 14-16), while in 2010 with the highest air temperature and the lowest amount of rainfall in the first ten-day period of June, the plants produced the greatest weight of leaves when Tytanit® was applied at a dose of 0.4 $dm^3 ha^{-1}$ in the tuber formation stage (BBCH 41-43).

The growth of plants depended to a great extent on the weather conditions (tab. 4). Regardless of the experimental factors, the plants produced the greater above-ground biomass in 2010 and 2012, with the higher air temperature in May, than in the cold year 2009.

Leaf weight ratio (LWR) and leaf area ratio (LAR). Tytanit® had a significant effect on the plant growth indices: leaf weight ratio (LWR) and leaf area ratio (LAR). With the Tytanit® application, the LWR was lower, on average, in the three years of the study by 0.017 $g g^{-1}$, and the LAR by 0.30 $cm^2 g^{-1}$, compared with the control object without the growth stimulant (tab. 3).

The LWR and LAR were cultivar-dependent (tab. 4). Regardless of the treatment (with or without Tytanit®), the LWR and LAR were higher for 'Miłek' cultivar than for the 'Lord' cultivar. Tytanit® had a greater effect on the LAR for the 'Lord' cultivar than for the 'Miłek' cultivar (tab. 9). The differences were higher under thermal and moisture contitions in 2010 and 2012 than in the 2009. The treatment and cultivar interaction effect on the LWR was not statistically confirmed.

A Tytanit® dose had no effect on the LWR and LAR (tab. 4). The cultivar and Tytanit® dose interaction effect on the LWR was not statistically confirmed. The performed study demonstrated a significant effect of the interaction of the year, cultivar and Tytanit® dose on the LAR (tab. 10). In the coldest and very moist growing season of 2009, the LAR for 'Lord' cultivar was higher when the growth stimulant was applied at the dose of 0.2 $dm^3 ha^{-1}$, and for 'Miłek' cultivar at the dose of 0.4 $dm^3 ha^{-1}$.

LWR and LAR depended on the date of Tytanit® application (tab. 4). The LWR was the highest when the growth stimulant was applied twice, i.e. in the leaf development stage (BBCH 14-16) and in the

Table 7. Above-ground plant biomas and tuber weight in relation to the year, cultivar and date of Tytanit® application

Date of Tytanit® application	Year and cultivar							
	2009		2010		2012		mean	
	Lord	Miłek	Lord	Miłek	Lord	Miłek	Lord	Miłek
Weight of leaves (g)								
BBCH 14-16	176 a	222 a	216 a	194 b	237 a	258 a	210 a	224 a
BBCH 41-43	176 a	182 b	200 ab	235 a	242 a	266 a	206 a	228 a
BBCH 14-16 + BBCH 41-43	167 a	164 b	177 b	196 b	242 a	267 a	196 a	215 a
Weight of stems (g)								
BBCH 14-16	260 a	246 a	384 a	235 b	346 a	261 a	330 a	247 a
BBCH 41-43	264 a	188 b	340 a	321 a	330 a	274 a	312 a	261 a
BBCH 14-16 + BBCH 41-43	237 a	190 b	268 b	228 b	320 a	280 a	275 a	233 a
Tuber weight (g)								
BBCH 14-16	638 a	680 a	662 a	679 a	555 a	714 a	618 a	691 a
BBCH 41-43	623 a	677 a	680 a	625 ab	588 a	647 a	630 a	650 a
BBCH 14-16 + BBCH 41-43	608 a	578 a	543 b	601 b	578 a	695 a	576 a	625 a

Means within columns followed by the same letters do not differ significantly at $P \le 0.05$

Table 8. Weight of leaves, leaf weight ratio (LWR) and leaf area ratio (LAR) in relation to the year, dose and date of Tytanit® application

Date of Tytanit® application	Year and Tytanit® dose							
	2009		2010		2012		mean	
	0.2 $dm^3 ha^{-1}$	0.4 $dm^3 ha^{-1}$	0.2 $dm^3 ha^{-1}$	0.4 $dm^3 ha^{-1}$	0.2 $dm^3 ha^{-1}$	0.4 $dm^3 ha^{-1}$	0.2 $dm^3 ha^{-1}$	0.4 $dm^3 ha^{-1}$
Weight of leaves (g)								
BBCH 14-16	198 a	201 a	210 a	200 a	248 a	248 a	218 a	216 a
BBCH 41-43	164 b	194 a	221 a	214 a	254 a	253 a	213 a	220 a
BBCH 14-16 + BBCH 41-43	150 b	200 a	203 a	170 b	264 a	245 a	206 a	205 a
Leaf weight ratio ($g\ g^{-1}$)								
BBCH 14-16	0.453 a	0.430 a	0.382 b	0.440 a	0.452 a	0.456 a	0.429 b	0.442 a
BBCH 41-43	0.450 a	0.445 a	0.398 b	0.397 a	0.465 a	0.469 a	0.438 b	0.437 a
BBCH 14-16 + BBCH 41-43	0.455 a	0.451 a	0.450 a	0.426 a	0.463 a	0.450 a	0.456 a	0.443 a
Leaf area ratio ($cm^2\ g^{-1}$)								
BBCH 14-16	14.03 a	14.16 a	13.25 b	14.63 a	14.45 a	14.86 a	13.91 b	14.55 a
BBCH 41-43	14.09 a	13.85 a	14.52 a	13.93 b	15.03 a	15.17 a	14.82 a	14.32 a
BBCH 14-16 + BBCH 41-43	14.03 a	14.39 a	14.54 a	13.60 b	14.89 a	14.66 a	14.49 a	14.22 a

Means within columns followed by the same letters do not differ significantly at $P \le 0.05$

Table 9. Leaf area ratio (LAR) and tuber weight in relation to the year, treatment and cultivar

Treatment	Year and cultivar							
	2009		2010		2012		mean	
	Lord	Miłek	Lord	Miłek	Lord	Miłek	Lord	Miłek
Leaf area ratio (cm^2 g^{-1})								
Without Tytanit®	13.25 a	15.72 a	13.93 a	14.30 b	14.14 a	16.76 a	13.77 a	15.59 a
With Tytanit®	13.05 a	15.40 a	12.88 b	15.28 a	13.45 b	16.24 b	13.12 b	15.64 a
Tuber weight (g)								
Without Tytanit®	584 b	698 a	577 b	557 b	421 b	664 a	527 b	640 a
With Tytanit®	623 a	645 b	628 a	635 a	574 a	686 a	608 a	655 a

Means within columns followed by the same letters do not differ significantly at $P \leq 0.05$

Table 10. Leaf area ratio (LAR) and tuber weight in relation to the year, cultivar and Tytanit® dose

Tytanit® dose	Year and cultivar							
	2009		2010		2012		mean	
	Lord	Miłek	Lord	Miłek	Lord	Miłek	Lord	Miłek
Leaf area ratio (cm^2 g^{-1})								
0.2 dm^3 ha^{-1}	12.89 b	15.75 a	12.98 a	15.23 a	13.44 a	16.14 a	13.10 a	15.71 a
0.4 dm^3 ha^{-1}	13.21 a	15.05 b	12.78 a	15.32 a	13.45 a	16.34 a	13.15 a	15.57 a
Tuber weight (g)								
0.2 dm^3 ha^{-1}	585 b	661 a	653 a	670 a	608 a	667 a	615 a	666 a
0.4 dm^3 ha^{-1}	661 a	629 a	604 b	600 b	539 b	704 a	602 a	644 a

Means within columns followed by the same letters do not differ significantly at $P \leq 0.05$

Table 11. Correlation coefficient between the tuber weight and plant growth characteristics

Plant growth characteristics	Treatment	
	without Tytanit®	with Tytanit®
Plant height	–0.5734*	–0.2860
Weight of leaves	0.1964	0.2122
Weight of stems	–0.7023*	–0.4465
Leaf weight ratio (LWR)	0.4962*	0.5608*
Leaf area ratio (LAR)	0.5287*	0.6816*

* Significant at $P \leq 0.05$

tuber formation stage (BBCH 41-43) and the LAR was the highest when the growth stimulant was only applied in the tuber formation stage (BBCH 14-16). The date of Tytanit® application had the greatest effect on the LWR in 2010 with the highest air temperature and, at the same time, the lowest rainfall in the first ten-day period of June (tab. 6). The cultivar and date of Tytanit® application interaction effect on LWR and LAR was not statistically confirmed.

The performed study demonstrated a significant effect of the interaction of the dose and the date of Tytanit® application on both the LWR and LAR (tab. 8). The date of treatment had a greater effect on the LWR and LAR when Tytanit® was applied at a dose of 0.2 dm^3 ha^{-1}, particularly in 2010 with the highest air temperature and, at the same time, the lowest rainfall in the first ten-day period of June.

The LWR and LAR depended to a great extent on the weather conditions (tab. 4). Regardless of the experimental factors, the LWR and LAR was highest in the warm and moderately wet growing season of 2012.

Tuber weight. Tytanit® had a significant effect on the tuber weight per plant described in the work by Kalinowski and Wadas [2017]. In the three years of the study, the tuber weight per plant was higher by 48 g (8%), on average, compared to the control object without this plant growth stimulant (tab. 3).

Tuber weight per plant was cultivar-dependent (tab. 4). Regardless of the treatment (with or without Tytanit®), the tuber weight per plant was higher for the 'Miłek' cultivar. 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 (tab. 9). With the Tytanit® application, the tuber weight per plant of 'Lord' cultivar was higher, on average, in the three years study by 81 g (15%) compared to the cultivation without the growth stimulant. For the 'Miłek' cultivar, the differences were smaller and not statistically confirmed. Tytanit® caused an increase in the tuber weight per plant of 'Miłek' cultivar only in 2010 with the highest air temperature and the periodically water shortage in June. In that year, with the Tytanit® application, the tuber weight per plant of the 'Miłek' cultivar was higher by 78 g (14%), on average, compared to the cultivation without the growth stimulant.

Tytanit® dose had no effect on the tuber weight per plant (tab. 4). The study demonstrated a significant effect of the interaction of the year, cultivar and Tytanit® dose on the tuber weight per plant (tab. 10). In the cold and very moist growing season of 2009, after the application of 0.4 dm^3 ha^{-1} of Tytanit®, the tuber weight per plant of 'Lord' cultivar was higher by 76 g (13%) compared to the dose of 0.2 dm^3 ha^{-1}.

The date of Tytanit® application had a significant effect on the tuber weight per plant (tab. 4). With the single application of the growth stimulant, the tuber weight per plant did not differ significantly in either the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). With double Tytanit® application (in the leaf development stage and with a repeated treatment in the tuber formation stage) the tuber weight per plant was, on average, lower by 48 g (8%) compared to a single treatment performed on each of these dates. The date of Tytanit® application had the greatest effect on the tuber weight per plant under thermal and moisture conditions in 2009 and 2010, less favourable for the early crop potato culture, than in the warm and moderately wet growing season of 2012 (tab. 6). The study demonstrated a significant effect of the interaction year, cultivar and date of Tytanit® application on the tuber weight per plant (tab. 7). In the 2010 with the highest air temperature, at the same time, the lowest rainfall in the first ten-day period of June, the date of growth stimulant application had a greater effect on the tuber weight per plant for the 'Lord' cultivar. The dose and date of Tytanit® application interaction effect on the tuber weight per plant was not statistically confirmed.

The tuber weight per plant was significantly positive correlated with LWR and LAR, both in the cultivation with and without Tytanit® (tab. 11). It was also found significant and negative correlation between the tuber weight and the length and weight of stems in the cultivation without this growth stimulant.

DISCUSSION

A condition for achieving a high potato yield on an early harvest date is (in addition to the proper selection of very early-maturing cultivars and the pre-sprouting of seed potatoes) to provide plants with good growth conditions. Water shortage during the tuber bulking period decreases yield to a larger extent than drought during other growth stages [van Loon 1981]. 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 of the cultivar area. Titanium exhibits properties of a biostimulant. Titanium applied via roots or leaves stimulates plant growth in a species-specific manner [Pais 1983, Grenda 2003, Du et al. 2010]. Plant growth and development are important variables in the analysis of the effects of growth stimulants on the yielding of crops and the optimisation of crop production. A study carried out in China demonstrated that the foliar application of titanium stimulated the growth of potato plants [Tan and Wang 2011], which was confirmed in the present study. Following the Tytanit® application, the plants were higher and produced a greater above-ground biomass than in the cultivation without the growth stimulant. Studies of other authors demonstrated a favourable effect of Tytanit® on the vegetative growth of tomato [Dobromilska 2007], rape [Kováčik et al. 2014] and bedding plants [Whitted-Haag et al. 2014].

Titanium exhibits favourable physiological effects on plants only at low concentrations. At higher concentrations, it may exhibit toxic effects. The titanium amount exhibiting either stimulating or toxic effects depends, *inter alia*, on the plant species and age [Duman and Ernst 1988, Kužel et al. 2003]. In the present study, a Tytanit® dose (0.2 dm^3 ha^{-1} or 0.4 dm^3 ha^{-1}) had no effect on the plant height but affected the amount of produced biomass under stress conditions. Under thermal and moisture conditions unfavourable to potato cultivation for an early crop, a greater increase in the above-ground plant biomass was the result of a dose of 0.4 dm^3 ha^{-1}. A similar relationship has been demonstrated by other authors. A Tytanit® dose of 0.4 dm^3 ha^{-1} stimulated the production of rape biomass more strongly than a dose of 0.2 dm^3 ha^{-1} [Kováčik et al. 2014].

The date of Tytanit® application had a greater effect on the length and weight of stems than on the weight of leaves. The plants were higher and produced a greater biomass of stems 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 leaf development stage and with repeated treatment in the tuber formation stage), the plants were shorter and the weight of their stems was lower. A positive correlation was found between the tuber yield and the plant height, stems per plant and main stem diameter [Arslan 2007, Abraham et al. 2014, Darabad 2014].

Plant growth is characterised by the leaf weight ratio (LWR) and the leaf area ratio (LAR). These indices are determined by the genetic features of a cultivar and plant growth stage, but their values can be modified by weather conditions and agricultural factors [Zrůst et al. 1999; Van Delden et al. 2000; Rykaczewska 2004], which was confirmed in the present study. Tytanit® had a significant effect on the share of assimilation organs in the whole plant weight and on the weight per unit leaf area. With the Tytanit® application, the LWR and LAR were lower than in the cultivation without the growth stimulant. The LAR decreases almost linearly with the growth of plants. This results from the reduction in the share of assimilating tissues in the whole plant weight. During ontogenesis, the share of assimilation organs in a whole plant weight (LWR) decreases faster than the weight per unit leaf area (LAR). A transient increase in the LAR value may be a result of a sudden improvement in the environmental conditions, e.g. following a period of drought or ground frosts [Pietkiewicz 1985; Rykaczewska et al. 2004]. According to Camargo et al. [2015], the LAR was the highest when the plants reached full coverage of the soil.

The Tytanit® dose (0.2 dm^3 ha^{-1} or 0.4 dm^3 ha^{-1}) had no effect on the share of assimilation organs in the whole plant weight (LWR) and on the weight per unit leaf area (LAR). Only in the cold and very moist year of 2009, the share of assimilation organs in the whole plant weight was higher following the application of 0.2 dm^3 ha^{-1} of Tytanit, while in the warmer year of 2010, with deficient rainfall at the beginning of June, the application of a higher dose of the growth stimulant resulted in an increase in the share of assimilation organs in the whole plant weight.

The weight per unit leaf area (LAR) depended to a greater extent on the date of growth stimulant application. The LAR was the highest when Tytanit® was only applied once in the tuber formation stage (BBCH 41-43) and the LWR was the highest when Tytanit® was applied twice, i.e. in the leaf development stage (BBCH 14-16) and in the tuber formation stage (BBCH 41-43). A higher LAR with a lower LWR suggests that with the application of the growth stimulant in the tuber formation stage (BBCH 41-43), the leaves were thinner and more delicate. The date of performance had a greater effect on the share of assimilation organs in the whole plant weight, and on the weight per unit leaf area, when Tytanit® was used at a dose of 0.2 dm^3 ha^{-1}.

The Tytanit® application caused an increase in the tuber weight per plant, which was confimed in a study carried out in southeast Lithuania on Haplic Luvisol [Asakaviciute and Lisova 2009]. A positive correlation was found between the tuber yield and the tuber weight per plant [Abraham et al. 2014, Darabad 2014]. The tuber weight per plant in the greater extent depended on the date of Tytanit® application than on the Tytanit® dose. Potato plants produced greatest tuber weight when Tytanit® was only applied once in the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). With double Tytanit® application (i.e. in the leaf development stage and with repeated treatment in the tuber formation stage) the tuber weight per plant was lower. In a study carried out in southeast Lithuania, the tuber weight per plant was greater with two Tytanit® applications (at the beginning of crop cover – BBCH 31 and at the beginning of flowering – BBCH 60-62) in the dose of 0.2 dm^3 ha^{-1} [Asakaviciute and Lisova 2009]. The tuber weight per plant was positive correlated with the LWR and LAR. Zrůst and Cepl [1991] found a significant relation between potato tuber yield and the LAR, particularly for leaf type cultivars.

CONCLUSIONS

Following the Tytanit® application, the plants were higher and produced a greater above-ground biomass and tuber weight, however, the leaf weight ratio (LWR) and leaf area ratio (LAR) were lower than in the cultivation without the growth stimulant. Tytanit® had a greater effect on the LAR and tuber weight for the 'Lord'cultivar than for the 'Miłek' cultivar. The Tytanit® dose (0.2 dm^3 ha^{-1} or 0.4 dm^3 ha^{-1}) had no effect on the plant height, above-ground biomass and tuber weight. A double Tytanit® application, i.e. the first one in the leaf development stage (BBCH 14-16) and a repeated treatment in the tuber formation stage (BBCH 41-43), resulted in a reduction in the length and weight of stems and tuber weight as compared with a single treatment performed either in the leaf development stage (BBCH 14-16) or in the tuber formation stage (BBCH 41-43). The date of Tytanit® application had no effect on the weight of leaves. The LAR was the highest when Tytanit® was only applied in the tuber formation stage (BBCH 41-43), and the LWR was the highest when Tytanit® was applied twice, i.e. in the leaf development stage and in the tuber formation stage (BBCH 14-16 + BBCH 41-43). A positive correlation was found between the tuber weight and LWR and LAR.

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