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DOES THE SULPHUR FERTILIZATION MODIFY MAGNESIUM AND CALCIUM CONTENT IN POTATO TUBERS (*Solanum tuberosum* L.)?

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Abstract. In case of sulphur shortage in the soil that element has a significant impact on yields of plants and their quality. The objective of the work was the impact of sulphur fertilization on content of Mg and Ca in the dry-mass and in yield of dry-mass of potato tuber. Experience in the field of potato head was in the years 2004–2006 by applying different kinds of sulphur (elemental and K_2SO_4) and rate (0, 25 and 50 kg·ha^{-1}). The content of Mg and Ca in the dry mass and Mg content in yield of dry mass of potato tuber was significantly determined by S fertilization. The highest content of Mg and Ca was found when using 25 kg S·ha^{-1} in elemental kind and 50 kg S·ha^{-1} in elemental and sulphur kind. Mg content in yield of dry mass of tubers increased S-elemental fertilization regardless of the rate, while this parameter of Ca no depended on S-fertilization. Sulphur fertilization in sulphate kind increased content S-SO_4 in the soil, while S-elemental fertilization in rate 50 kg·ha^{-1} decreased pH value of soil. Negatively correlation was between pH value of soil and Mg content in dry-mass of tuber. Negatively correlation was also between pH value of soil and Ca content in yield of dry mass of potato tubers.

Key words: *Solanum tuberosum* L, sulphate sulphur, elemental sulphur

INTRODUCTION

Potatoes (*Solanum tuberosum* L.) are the fourth most important food crop in the world, providing more edible food than the combined world output of fish and meat. Statistical Pole consumes annually 116 kg of potato products [Dzwonkowski et al. 2010]. Because of that high consumption the health value of potato varieties i.e. content of macro and micro-nutrients compounds is of great importance. Potato tubers contain 1–1.2% mineral compounds, the most basic being potassium, magnesium, calcium and phosphorus [Gugała et al. 2012]. Macroelements perform important building functions, are an integral part of enzymes, and play an important role as regulators of metabolic processes [Graham et al. 2007, White and Broadley 2005, 2009]. A recommended daily

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intake of Mg and Ca by man is around 300–400 and 800–1000 mg, respectively [Theobald 2005, Gugała et al. 2012]. Both the shortage and excess of the elements result in disturbed metabolism in plants and animals [Rivero al. 2003, Wang et al. 2008]. Magnesium and calcium contents in potato tubers are conditioned by varietal properties, soil, weather conditions during growth and agrotechnological practices, including mineral fertilization and weed control [Gugała and Zarzecka 2008, Wichrowska et al. 2009].

Clean air acts led to a drastic decrease of SO_2 emissions in Western Europe including Poland and macroscopic sulfur deficiency has become a widespread nutrient disorder in agricultural production [Haneklaus et al. 2003, Balik et al. 2009]. Sulphur is now viewed as the fourth major plant nutrient which crops absorb in amounts comparable to that of phosphorus. Sulfur fertilization increased yield of potato tubers, improved tuber quality (increased content of protein, starch, carotene, vitamin C, macro- and microelements) and resistance against *Streptomyces scabies* and *Rhizoctonia solani* [Klikocka et al. 2005, Klikocka 2009a, 2009b, 2010, Mishra and Srivastava 2004/5, Kumar et al. 2007]. Sulphur is an essential element in mineral nutrition of plants, especially high demand for sulphur, as: rape, onions, garlic, sugar beet [Klikocka 2010, 2011a]. Nurzyńska-Wierdak [2009] reported however, that the leaves of plants nourished with K_2SO_4 contained more nitrates and less Ca, Mg, Mn and Mo, as compared to KCl fertilization.

Because in recent years the soils in Poland have catastrophically low the content of availability sulphur (S-SO_4) [Siebielec et al., 2012] were conducted a study of sulphur suplementation for the cultivation of potatoes.

So far, however, no more information is available about the influence of the S supply on quality of potato tuber. Thus, it has been attempted to determine the effect of kind (sulphate and elemental) and dose (0, 25, 50 kg·ha^{-1}) of sulphur application on the content of Mg and Ca in the dry mass and in yield of dry mass of potato tuber.

MATERIALS AND METHODS

Field experiments with potatoes were conducted in the years 2004–2006 in a split plot design in fourfold repetition at Malice (N 50°42'; E 23°15'), a village near Zamość in Poland. The experiment was carried out on a leached brown earth with loamy silty soil texture (clay – 13%). Reaction of the soil, pH (0.01 M $CaCl_2$) value = 5.2. Content in the soil (g·kg^{-1} of soil) of C-total content was on average 7.4, N-total – 0.7; and (mg·kg^{-1} of soil) P – 41.7, K – 76.8, Mg – 30.8 and S-SO_4 – 10.1.

Surface plots for planting and observation was 30 m^2, in contrast for harvesting was 19.5 m^2 (3.0 m × 6.5 m). The Irga, medium-early, edible variety was used. The forecrop was Triticale in all of years of experimentation.

The following S treatments were tested: 0, 25 and 50 kg S·ha^{-1} as K_2SO_4 and as elemental S. The K supply was balanced by using KCl in adequate rates. Elemental S originated from the sulfur mine "Jeziórko" in Poland and was fine-ground in a mortar. Plants can get sulfur after oxidation to form S-SO_4. Currency converter S → S-SO_4 is 3, while S-SO_4 → S is 0.33.

After gathering of spring Triticale its used of 3 t·ha^{-1} straw from spring Triticale (as organic fertilization) and 46 kg N·ha^{-1} (urea $CO(NH_2)_2$) – for stabilization in ratio C:N) and were perkinded ploughing (20 cm, second or third decade of August). Spring field works were perkinded in the third decade of March, where shallow ploughing is used (15 cm). Every year, mineral fertilization in kg·ha^{-1} was applied pre-planting: N (as ammonium nitrate) – 100; P (as mineral superphosphate – triple granular) – 40; K (as potassium sulphate) – 116. Potato planting was carried out in the second decade of April. Row-space was 67.5 cm with 44.000 tubers per 1 ha planted. The distance between plants in a row amounted to 30 cm.

Potato planters are equipped with attachments to apply materials to control *Rhizoctonia solani* by metyl tolchlofos (Rizolex, 500 g a.i.·kg^{-1}, Sumitomo) in dose 10 g a.i. per 100 kg of tubers. Weed control was mechanical-chemical: mechanical treatments from potato planting until germination (harrowing, earthing up, and weeding). After germination was used herbicide metribuzin (Sencor 70 WP, 700 g a.i.·kg^{-1}, Bayer) in dose 0.350 g a.i.·ha^{-1} (Sencor – C_8H_{14}-ON_4S contained 15.0% of S, in this case is used 0.05 kg S·ha^{-1}).

Chemical application of fungicides for the control of *Phytophthora infestans* (late blight) and other foliage diseases were perkinded in accordance with the recommendations of the Institute of Plant Protection (IOR-Poland). The detailed methodology to protect potatoes before late blight and chrysometids described in the earlier work [Klikocka 2011b]. Tubers were harvested in the second decade of September.

Precipitation (April-September) were similar than the long-term average during tuber kindation in 2005–2006 years of experimentation. The sum of long-term average precipitation (1971–2005) is 329.8 mm, while in 2005 and 2006 values of 315.2 and 329.8 mm were determined. In 2004 sum of precipitation were higher than the long-term (fewer 54,3 mm). The sum of mean month temperatures (April-September) in analyzed period was higher than long-term. The sum of mean month temperatures 2901°C in the 2004 and 2949°C in 2005 and 3142°C in 2006; the long-term average is 2687°C. To characterize the weather conditions in years of research 2004–2006 calculated hydro-thermal coefficient of Sielianinow, which was accordingly: 2004 – 1.3 (quite dry), 2005 – 1.1 (quite dry), 2006 – 1.0 (dry), long-term 1971–2005 – 1.5 (quite wet).

Methodology for chemical analysis of soil and plant material is shown in table 1.

Table 1. Analytical methods for plant tissue materials and for soil

	Parameter	Method
Plant tissue materials	dry matter	During oven method (at 105°C)
	Mg, Ca	Extraction with 2 M HCl, determined by atomic absorption spectrophotometry (AAS)
Soil	pH	Potentiometrically in 0.01 M $CaCl_2$ suspension using a Methrohm 605 pH-meter
	S-SO_4	Extracted by 0.025 M KCl and determined by ion-chromatograph [Bloem et al.. 2002]

Collected in the experiment results summarizes in the lines-column blocks, where the lines were (1) sulphur fertilization (control, 25 SO_4, 25 S, 50 SO_4, 50 S), underlines – (2) years of study (2004, 2005, 2006) and for column (3) 4 repetition. So the summarized the results of the statistical analysis were. Null hypothesis (H_0) assumed that the control fertilization (NPK + 0 S) and sulfur fertilization (NPK + S) can be compared, because they give the same effect. However, the lack of similarity can be expressed in the form of an alternative hypothesis (H_1) (formula 1):

$$H_0 : \Lambda_{NPK} = \Lambda_{NPKS} \text{ against the alternative } (2^0)\ H_1 : V_{NPK} \neq V_{NPKS} \qquad (1)$$

$$F^0 \geq F\alpha \qquad\qquad F^0 < F\alpha$$

where:

H_0 – effects of the object are null, Λ – for each,
H_1 – effects of the object are different, V – existing
F^0 – test function F probability (F-Snedecor) distribution calculated in the analysis of variance
Fα – the distribution of the test function F (*α = 0.05, ** α = 0.01, *** α = 0.001)

To test the null hypothesis H_0 was used analysis of variance with test of F-Snedecor, and then calculated its distribution [Hanusz et al. 2003]. The significance of the differences was used the test of Tukey (α = 0.05). Were also the coefficient of variation (*CV%*) (the quotient of the standard deviation and mean). Correlation coefficients were also. In the statement, and the statistical study results used the Excel 7.0 and Statistica (StatSoft Polska ’97).

RESULTS AND DISCUSSION

Conducted analysis of variance showed that differences in content the magnesium and calcium in the dry mass and Mg content in yield of the dry mass of tubers and were statistically significant, the factors of experience differently effected on tested characteristics (tab. 2, 3).

Content of Mg in dry mass and yield of dry mass of potato tubers depended significantly on rate and kind of sulphur fertilization, its interaction and years of study. Rate 25 and 50 kg $S \cdot ha^{-1}$, regardless of the kind significantly and proportionate increased Mg content in dry-mass of tuber. But the highest Mg content in yield of dry-mass of tubers was when used 50 kg $S \cdot ha^{-1}$, regardless of the kind. The favourable form was S-elemental kind in comparison to a control object and sulphate kind, since significantly increased content of magnesium. In case of rate and kind interaction the highest content of Mg in dry-mass of tuber was observed after application of S-elemental kind, regardless of the rate and after application of sulphate kind in double rate. Content of Mg in yield of dry-mass of tubers was highest after application 50 kg $S \cdot ha^{-1}$, regardless of the kind. Weather conditions have had a significant impact on the size of the features. In the years 2004 and 2006 content of Mg in dry mass and in yield of dry mass of tubers was highest than in 2005 year.

Table 2. Results of statistical computation for content of magnesium and calcium in dry mass and yield of dry mass of potato tuber

Investigated features	Variable	SED	CV%	Estimation F	p-value	LSD α = 0,05
Content of magnesium in tuber (g kg^{-1})	R	0.07	7.10	19.98***	0.0001	0.05
	K	0.07	7.44	16.97**	0.0047	0.05
	R × K	0.07	7.53	11.66***	0.0001	0.06
	Y	0.04	4.20	6.05***	0.0001	0.05
	R × Y	0.09	9.07	10.25***	0.0001	0.08
	K × Y	0.08	8.77	5.55**	0.0021	0.08
Content of magnesium in d.m. tuber yield (kg ha^{-1})	R	0.95	4.40	7.25**	0.0030	1.02
	K	1.21	5.62	9.92***	0.0006	1.02
	R × K	1.20	5.56	6.55***	0.0003	1.33
	Y	0.80	3.69	4.82*	0.0127	1.02
	R × Y	1.50	7.08	8.89***	0.0001	1.78
	K × Y	1.44	6.73	3.42*	0.0219	1.78
Content of calcium in tuber (g·kg^{-1})	R	0.03	4.54	2.85	0.0753	n.s.
	K	0.03	4.25	2.51	0.0997	n.s.
	R × K	0.04	6.18	3.06*	0.0258	0.07
	Y	0.06	9.17	11.24***	0.0001	0.05
	R × Y	0.07	11.56	3.78*	0.0145	0.09
	K × Y	0.07	11.94	3.65*	0.0167	0.09
Content of calcium in d.m. tuber yield (kg ha^{-1})	R	0.32	2.23	0.65	0.5282	n.s.
	K	0.46	3.23	1.33	0.2814	n.s.
	R × K	0.66	4.63	1.59	0.1933	n.s.
	Y	1.37	9.63	11.49***	0.0001	1.15
	R × Y	1.53	10.65	2.33	0.0810	n.s.
	K × Y	1.60	11.23	2.28	0.0863	n.s.

Variable: R rate (df_1 = 2, df_2 = 27), K kind (df_1 = 2, df_2 = 27), RK rate × kind (df_1 = 4, df_2 = 45), Y years (df_1 = 2, df_2 = 45), RY rate × year (df_1 = 4, df_2 = 27), KY kind × year (df_1 = 4, df_2 = 27): where df_1 – degrees of variable freedom, df_2 – degress of error freedom, SED – standard error, CV% – coefficient of variation, estimation F of variance analysis, significant difference at (*α = 0,05, ** α = 0,01, *** α = 0,001), p-value of F-variance ratio, LSD – least significant difference, n.s.– not significant

In case sulphur fertilization on calcium content in dry mass of potato tubers no stated significantly direct influence. Just, interaction between kind and rate of sulphur fertilization differentiated content of Ca. Significantly more of Ca in dry-mass of tuber is stated after elemental sulphur application, regardless of rate, and after application of sulphate kind in rate 50 kg·ha^{-1}, in comparison to control object and sulphate kind in rate 25 kg·ha^{-1}. Sulphur fertilization no influenced content of Ca in yield of dry-mass of tubers. Years of study significantly influenced of Ca content in dry mass and Ca content in yield of dry-mass of tubers. It was noted that in the years 2004 and 2006 was smaller calcium content, while in 2005 the calcium content was higher. The opposite was of case of the Mg. Płaza [2004] found that for the best content of the macronutrients (N, P, K, Mg, Ca) in potato tubers turned out to be a warm year with high precipitation in August, and the small in September. Less positive was the year of a smaller amount of precipitation in August, and more in September. While the negative was the growing season, in which there has been a shortage of precipitation in August, and excess in September. This weather is not conducive to the concentration of macronutrients in potato tubers. In presented study the precipitation was respectively in years 2004, 2005, 2006: August – 71.9, 52.7, 144.8 mm, September – 36.3, 15.8, 0.8 mm. The data shows that, in the case of higher precipitation in August and in September the tubers contain more Mg, while at smaller rainfall in August and September tubers contain more calcium. Also the works by Gugała et al. [2012] as well as Wadas [2008] have confirmed that there is an effect of weather conditions on magnesium and calcium contents.

Table 3. The influence of sulphur fertilization on content in potato tubers (A) (g kg^{-1}) and content in tubers yield (B) (kg ha^{-1}) of Mg and Ca

S rate (kg ha^{-1})	S kind	Magnesium		Calcium	
		A**	B**	A	B
0 – control		0.90a	20.36a	0.63a	14.20a
25	SO_4	0.91a	20.27a	0.59a	13.14a
25	S	1.02b	22.62ab	0.67ab	14.76a
50	SO_4	1.01b	21.72a	0.67ab	14.69a
50	S	1.06b	22.78ab	0.68ab	14.26a
0 – control		0.90a	20.36a	0.63a	14.20a
25	mean	0.96b	21.44a	0.63a	13.95a
50	mean	1.04c	22.25b	0.68a	14.58a
0 – control		0.90a	20.36a	0.63a	14.20a
SO_4	mean	0.96b	20.99a	0.63a	13.81a
S	mean	1.04c	22.70b	0.68a	14.73a
Years	2004	0.99b	22.12b	0.61a	13.51a
Years	2005	0.93a	20.64a	0.72b	15.84b
Years	2006	1.01b	21.89b	0.62a	13.41a

**A: content in d.m. of tubers; B: content in d.m. of tubers yield

Compare features, depending on the applied rate and kind S-fertilization were very stable, with greater stability had calcium content than magnesium. Generally, the value of the tested features of potato was the most changed (*CV%*), and differentiated (NIR) in each of the years of research and by interaction of weather factors with S-fertilization than the direct effect of sulphur fertilization (tab. 2, 3).

Eppendorfer and Eggum [1994] and Singh et al. [1995] says that S application increased in tuber of total – N, P, K, Na, Ca, Mg, Zn Mn, Cu and Fe contents. Singh and Srivastava [1996] supplemented S for potato in dose of 20 kg·ha^{-1}, in the $CaSO_4$ kind and have demonstrated increase of iron in chloroplasts and higher content iron in tubers. Also El-Fayoumy and El-Gamal [1998] have studied that sulphur fertilization increased in tubers: carotene, vitamin C, starch, protein, micronutrients and reduced sugar content.

Table 4. Results of statistical computation for investigated features of potato and content of $S\text{-}SO_4$ in soil

Investigated features	Variable	SED	CV%	Estimation F	p-value	LSD α = 0,05
Tuber yield ($t\ ha^{-1}$)	R	0.93	3.47	5.20*	0.0123	1.13
	K	0.99	3.72	6.55**	0.0048	1.13
	R × K	0.99	3.70	3.11*	0.0242	1.60
	Y	1.73	6.43	15.67***	0.0001	1.13
	R × Y	1.57	5.84	0.94	0.4578	n.s.
	K × Y	1.73	6.50	0.57	0.6835	n.s.
Content of D.M. (%)	R	0.62	2.83	67.07***	0.0001	0.22
	K	0.51	2.32	56.42***	0.0001	0.22
	R × K	0.55	2.48	29.75***	0.0001	0.29
	Y	0.32	1.47	17.41***	0.0001	0.22
	R × Y	0.69	3.13	14.46***	0.0001	0.38
	K × Y	0.61	2.73	14.07***	0.0001	0.35
Yield of D.M. of tubers ($t\ ha^{-1}$)	R	0.12	1.96	1.95	0.1621	n.s.
	K	0.12	2.08	2.43	0.1069	n.s.
	R × K	0.21	3.54	3.21*	0.0210	0.33
	Y	0.30	5.11	11.16***	0.0001	0.23
	R × Y	0.26	4.39	1.10	0.3770	n.s.
	K × Y	0.28	4.70	0.20	0.9359	n.s.
Content in soil $S\text{-}SO_4$ ($mg \cdot kg^{-1}$)	R	2.44	8.81	2.43	0.1070	n.s.
	K	3.23	11.66	5.58*	0.0116	3.34
	R × K	3.32	11.96	3.47*	0.0149	5.07
	Y	6.68	24.10	23.49***	0.0001	3.34
	R × Y	6.00	21.68	0.46	0.7611	n.s.
	K × Y	6.88	25.29	2.73*	0.0498	7.24

Variable: R rate (df_1 = 2, df_2 = 27), K kind (df_1 = 2, df_2 = 27), RK rate × kind (df_1 = 4, df_2 = 45), Y years (df_1 = 2, df_2 = 45), RY rate × year (df_1 = 4, df_2 = 27), KY kind × year (df_1 = 4, df_2 = 27): where df_1 – degrees of variable freedom, df_2 – degress of error freedom, SED – standard error, CV% – coefficient of variation, estimation F of variance analysis, significant difference at (*α = 0,05, ** α = 0,01, *** α = 0,001), p-value of F-variance ratio, LSD – least significant difference, n.s. – not significant

Conducted analysis of variance showed that differences in yield of tubers, the dry-mass content of tubers were statistically significant (tab. 4, 5). Generally sulphur fertilization have positively changed the tuber yield of potato and decreased content of dry-mass. Not only the influence of sulphate sulfur in rate of 25 $kg \cdot ha^{-1}$ on the yield of tubers. However, a significant influence on the increase of tubers yield had each rate and kind of sulphur in relation to control object (without sulphur). The highest content of dry-mass was received in a control object, and each rate and kind of S-fertilization decreased the tested characteristic. The highest yield of dry-mass were received after using of 25 kg $S \cdot ha^{-1}$ application in sulphate kind, in other cases it was significantly smaller. Tested characteristics under the influence of sulfur fertilization were stable. Generally, the value of the test property of potato was the most changed *(CV%)*, and differentiated (NIR) in each of the years of study by weather and by interaction of weather with S-fertilization than by the direct effect of S-fertilization (tab. 3, 4).

Table 5. The influence of sulphur fertilization on the yield of potato tubers and dry mass and parameter of soil

S rate ($kg \cdot ha^{-1}$)	S kind	Tuber yield ($t \cdot ha^{-1}$)	Content of D.M. (%)	Yield of D.M. of tubers ($t \cdot ha^{-1}$)	pH (0.01 M $CaCl_2$)	Content $S\text{-}SO_4$ in soil ($mg\ kg^{-1}$)
0 – control		25.56a	22.75c	5.81a	5.25–5.33	24.78a
25	SO_4	28.06ab	22.38b	6.28b	5.18–5.40	28.73ab
25	S	26.17a	22.10b	5.78a	5.19–5.32	25.83a
50	SO_4	27.02ab	21.50a	5.80a	5.20–5.42	33.07b
50	S	27.44ab	21.52a	5.90a	5.08–5.21	26.26a
0 – control		25.56a	22.75c	5.81a	5.25–5.33	24.78a
25	mean	27.12b	22.24b	6.03a	5.21–5.31	27.28a
50		27.23b	21.51a	5.85a	5.15–5.32	29.66a
0 – control		25.56a	22.75b	5.81a	5.25–5.33	24.78a
SO_4	mean	27.54b	21.94a	6.04a	5.24–5.32	30.90b
S		26.81b	21.81a	5.84a	5.15–5.23	26.05a
Years	2004	25.03a	22.32b	5.58a	5.26–5.33	23.50a
	2005	27.07b	22.14b	5.99b	5.26–5.38	35.44b
	2006	28.46c	21.69a	6.17bc	5.23–5.35	24.26a

The positive impact of sulphur fertilization (in the kind of: potassium sulphate, ammonium sulphate, sufran plus, single superphosphate, gypsum and elemental sulphur) on potato yields has multiple authors: Lalitha et.al. [1997], Grocholl and Scheid [2002], Carew et al. [2009]. El-Fayoumy and El-Gamal [1998], Pickny and Grocholl [2002] recommend the use of elemental sulphur for potatoes in dose from 36 to 80 $kg \cdot ha^{-1}$. However, some studies have shown a reduction in the yield of potato tubers as a result of the application of elemental sulphur [Eppendorfer and Eggum 1994]. Wang et al. [2008] says that in S-deficient soil, application of S fertilizer can significantly increase tuber yield and starch content of potato, while leading to a decrease in tuber N concentration due to an increase in dry matter production. While Kumar et al. [2007] reported that tuber dry-matter percentage did vary with K-sources and sulphate and nitrate sources of K gave higher values than K-chloride.

In order to assess the influence of sulfur fertilization on content of Mg and Ca in potato in table 3 and 4 presented pH soil value and $S\text{-}SO_4$ content in the soil after harvesting the potatoes. Generally, the S-fertilization hat significantly influence on $S\text{-}SO_4$ content in the soil. Sulphur contents in the soil depends more on kind than the rate of S-application and was highest after applying 50 $kg \cdot ha^{-1}$ in S-elemental kind. Reaffirm in this case, numerous reports, talking about the gradual release of sulphates of elemental sulphur [Klikocka 2010]. This phenomenon affected noticeably on the reduction of pH value of soil (tab. 4). Generally, sulphur fertilization in sulphate kind increased content $S\text{-}SO_4$ in the soil, while S-elemental fertilization in rate 50 $kg \cdot ha^{-1}$ decreased pH value of soil (tab. 5). Content of $S\text{-}SO_4$ in soil in 2004 year positively correlated with content and uptake of Mg by dry-mass of tuber. Negatively correlation was between pH value of soil and Mg content in dry-mass of tuber. Negatively correlation was also between pH value of soil and Ca content in dry mass yield of potato tubers. In addition, it was found a negatively correlation between pH value of soil and tuber yield and positively correlation between pH value of soil and content of dry-mass in potato tubers. Also the content of Mg in tubers correlated negatively with the dry-mass content in the tubers. Between Mg and Ca in tubers not found significantly correlation (tab. 6, 7).

Table 6. Significant correlation coefficients between elements in plant and soil properties and yield of potato tubers (mean of 2004–2006)

Specification (n = 60)	Yield of tubers	Content of dry mass	Yield of dry mass	Elements in tubers			
				Mg		Ca	
				C.	R.	C.	R.
pH of soil	-0.28*	0.44	-	-0.25	-	-0.29	-0.25
S-SO_4 in soil	-	-	-	-	-	-	-
Yield of tubers	-	-0.44	0.93	-	-	-	-
Content of dry mass	-	-	-	-0.46	-	-	-
Yield of dry mass	-	-	-	-	-	-	-

C – content in d.m. of tubers; R – content in yield of d.m. of tubers
* – Significant coefficients

Table 7. Significant correlation coefficients between elements in plant and pH and content of SO_4 in soil

Specification (n = 20)		Yield of tubers	Elements in tubers			
			Mg		Ca	
			C.	R.	C.	R.
pH of soil	2004	-0.44	-	-	-	-
	2005	-	-	-	-	-
	2006	-	-	-	-0.68	-0.62
SO_4 in soil	2004	-	0.58	0.53	-	-
	2005	-	-	-	-	-
	2006	-	-	-	-	-

An explanation in tab. 6

White and Bradley [2005, 2009] reported, that magnesium is present as a divalent cation in the soil solution, which, because it binds less avidly to soil particles than other cations, is prone to leaching. This is considered to be an important factor influencing Mg phytoavailability in shallow or coarse-textured soils. Magnesium deficiency in plants occurs worldwide, especially on strongly acidic soils and is aggravated by high concentrations of competing cations, particularly Al^{3+} and Mn^{2+}, in the soil solution. On alkaline soils, carbonate formation and excess Ca, potassium (K) and Na reduce Mg phytoavailability. It is also possible that the incidence of Mg deficiency in crop plants is increasing as a result of intensive crop production without concomitant Mg fertilization. Plants rarely lack a Ca supply from the soil solution sufficient for growth, and Ca^{2+}

concentrations in the rhizosphere solution generally lie in the millimolar range [White and Bradley 2005, 2009]. Hovewer, Ca deficiency can occur in plants growing on highly weathered tropical soils, because of their low total Ca content, on strongly acidic soils, where Al^{3+} may inhibit Ca^{2+} uptake, and on sodic or saline soils, where excessive sodium (Na^+) inhibits Ca^{2+} uptake. Sodic or saline soils occur worldwide, but mostly in the arid subtropics. In addition, several costly Ca-deficiency disorders occur in horticulture, which arise when sufficient Ca is temporarily unavailable to developing tissues. The supply of Ca^{2+} to field crops is determined by various aspects of soil chemistry including cation exchange capacity, representation of Ca in the base cation pool, the rate at which mineralization of soil organic matter releases Ca^{2+}, and the pH of the soil solution.

Scherer [2001], Aulakh [2003], Jaggi et al. [2005] reported that the S deficiency in soils in several parts of the world led to the use of fertilizer S to enhance the production and quality of crops. Among S-containing fertilizers, elemental S (S°) is becoming increasingly popular in field crops. Use of S° helps to reduce leaching and run-off losses, leaving prolonged residual effects on the S nutrition of the succeeding crop. The biochemical oxidation of S° produces H_2SO_4, which decreases soil pH value and solubilizes $CaCO_3$ in alkaline calcareous soils to make soil conditions more favorable for plant growth, including the availability of plant nutrients [Jaggi et al. 2005, Klikocka et al. 2005, Klikocka 2010]. Thus, application of S° to alkaline-calcareous soils could assist in correcting iron chlorosis. Soil pH is known to regulate bioactivity and availability of nutrients to plants, because H^+ protons are involved in chemical equilibrium [Jaggi et al. 2005]. The use of S° in alkaline soils reduces soil pH value, which may create favorable conditions for the availability of plant nutrients, especially P [Aulakh 2003, Kulczycki 2003]. As reported in the presented research sulphur fertilization, especially in the elemental kind resulted in lowering the pH value and the important increase of content nutrients in tubers of potatoes. This phenomenon was in the presented studies. Therefore, you should recommend supplementation of mineral fertilization under potatoes in sulphur, particularly in elemental kind.

On the basis of studies you can propose an optimal dose of elemental sulphur under the potato in quantities of 50 kg $S \cdot ha^{-1}$. It will provide extra into the soil the amounts of 39.9 $mg \cdot kg^{-1}$ $S\text{-}SO_4$ (assuming that the average depth of the topsoil is 25 cm and soil density is 1.5 $Mg \cdot m^{-3}$). At present, 90% of the soil profiles in Poland contains below 16.5 $mg \cdot kg^{-1}$ $S\text{-}SO_4$, which causes them to qualify in the form of low-sulphur, and this involves the possibility of a deficit of sulphur in these soils [Siebelec i in. 2012]. The soil on which the experiment was conducted included 10.1 $mg \cdot kg^{-1}$ $S\text{-}SO_4$, so it was a very low content.

CONCLUSIONS

The content of Mg and Ca in the dry-mass and content of Mg in yield of dry mass of potato tuber was significantly determined by S fertilization. The highest content of Mg and Ca was found when using 25 kg $S \cdot ha^{-1}$ in elemental kind and 50 kg $S \cdot ha^{-1}$ in elemental and sulphur kind. Mg content in yield of dry mass tubers increased elemental sulphur regardless of the dose, while this parameter of Ca no depended on sulphur fertilization.

The yield of tubers and content of dry-mass depend substantially on the rate and kind of fertilizer. The highest tuber yield was found when 25 $kg \cdot ha^{-1}$ S was applied in sulphate kind and 50 $kg \cdot ha^{-1}$ S applied in sulphate and elemental kind. The yield of dry-mass was highest when 25 kg $S \cdot ha^{-1}$ was applied in sulphate kind.

Sulphur fertilization in sulphate kind increased content $S\text{-}SO_4$ in the soil, while S-elemental fertilization in rate 50 $kg \cdot ha^{-1}$ decreased pH value of soil. Content of $S\text{-}SO_4$ in soil in 2004 year positively correlated with content and uptake of Mg by dry-mass of tuber. Negatively correlation was between pH value of soil and Mg content in dry-mass of tuber. Negatively correlation was also between pH value of soil and Ca content in yield of d.m. of tubers. In addition, it was found a negatively correlation between pH value of soil and tuber yield and positively correlation between pH value and content of dry-mass in potato tubers. Also the content of Mg in tubers correlated negatively with the dry-mass content in the tubers. Between Mg and Ca in tubers not found significantly correlation.

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CZY NAWOŻENIE SIARKĄ MODYFIKUJE ZAWARTOŚĆ MAGNEZU I WAPNIA W BULWACH ZIEMNIAKA (*Solanum tubersosum* L.)?

Streszczenie. W warunkach niedoboru siarki w glebie nawożenie tym pierwiastkiem ma istotny wpływ na plonowanie roślin i ich jakość. Celem pracy była ocena wpływu dawki i rodzaju siarki na zawartość w suchej masie i pobranie przez plon suchej masy bulw ziemniaka Mg i Ca. Doświadczenie polowe z ziemniakiem prowadzono w latach 2004–2006, stosując różne rodzaje siarki (siarka elementarna i K_2SO_4) oraz dawki (0, 25 i 50 kg·ha^{-1}). Aplikacja siarki istotnie wpłynęła na zawartość Mg i Ca w suchej masie bulw i zawartość Mg w plonie suchej masy bulw. Największą zawartość Mg i Ca stwierdzono po zastosowaniu 25 kg S·ha^{-1} w formie elementarnej i 50 kg S·ha^{-1}, bez względu na formę. Wpływ na zwiększoną zawartość Mg w plonie s.m. bulw miało zastosowanie siarki elementarnej bez względu na formę, natomiast cecha ta w przypadku wapnia nie zależała od nawożenia siarką. Nawożenie siarką w formie siarczanu bez względu na dawkę zwiększało zawartość formy przyswajalnej SO_4 w glebie, natomiast siarki elementarnej, zwłaszcza w dawce 50 kg·ha^{-1}, wpływało na obniżenie odczynu (pH) gleby. Ujemna korelacja wystąpiła pomiędzy odczynem gleby (pH) a zawartością Mg w suchej masie bulw oraz pomiędzy pH gleby a zawartością Ca w s.m. i w plonie s.m. bulw ziemniaka.

Słowa kluczowe: *Solanum tubersosum* L, siarka siarczanowa, siarka elementarna

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