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GENOTYPE AND ENVIRONMENTAL VARIABILITY OF CHEMICAL ELEMENTS IN POTATO TUBERS

REVIEW ARTICLE

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Abstract. The scope of genetic variation in concentrations of minerals in potato tubers and effects of mineral fertilizers application, pesticides, growth regulators on the mineral content and the relationships of these elements in potato tubers, was analyzed. The study discussed the phenotypic variation range determined by genetic and environmental variability. The hypothesis presupposes that increased yields generated either by the application of mineral fertilizers and/or the use of cultivars with higher fertility may lead to a reduction in the concentration of minerals in potato tubers, was verified in the study.

Key words: biotic factors, fluctuation, ion relations, macronutrients, microelements, potato, *Solanum* genotypes,

INTRODUCTION

Man requires at least 22 mineral elements for well-being [White and Broadley 2003, White & Broadley 2005, Sawicka 2016). It is estimated that more than 60% of the world's population suffers from a deficiency of iron (Fe), over 30% from deficiency of zinc (Zn), 30% from iodine (I) and about 15% from selenium (Se) [Welch & Graham 2002, White & Broadley 2005]. Deficiencies of calcium (Ca), magnesium (Mg), and copper (Cu) are common for both developed and developing countries. This is due to achieving products from areas of low abundance in minerals, consumption of foods from plants/tissue with inherently low minerals content or consuming sophisticated cuisine. In particular, it appears that anemia due to Fe deficiency, disorders due to zinc

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(Zn) deficiency, and disorders of Ca, have dramatically increased in the human population as influenced by traditional diets dominated by legumes, vegetables, and fruits, as well as diets dominated by cereals [Sawicka 1991, Graham *et al*. 2001, Welch & Graham 2002, White & Broadley 2003, Broadley *et al*. 2007, Sawicka 2016]. Therefore in the study discussed the phenotypic variation range determined by genetic and environmental variability. The hypothesis presupposes that increased yields generated either by the application of mineral fertilizers or the use of cultivars with higher fertility may lead to a reduction in the concentration of minerals in potato tubers, was verified in the study.

GENETIC VARIABILITY OF MINERAL ELEMENTS CONTENT IN POTATO TUBERS

There is considerable genetic variation in the concentration of minerals in tubers, both between *Solanum* cultivars and species (Table 1).

Table 1. The mineral content of 200 g fresh weight of potatoes and its contribution to the U.S. Dietary Reference Intake (DRI)*

Mineral content	Unit	Reference Daily Intake (DRI)	US potatoes	UK potatoes	Percent DRI
N	mg	**ns	–	660.0	–
S	mg	ns	–	60.0	–
K	mg	4700.0	850.0	720.0	18.0
Cl	mg	2300.0	–	132.0	–
Ca	mg	1000.0	22.0	10.0	2.2
P	mg	700.0	118.0	74.0	17.0
N a	mg	1500.0	12.0	14.0	0.8
Mg	mg	420.0	45.0	34.0	11.0
Fe	mg	8.0	1.4	0.8	18.0
Zn	mg	11.0	0.6	0.6	5.5
Mn	mg	2.3	0.3	0.2	13.0
Cu	µg	900.0	231.0	160.0	26.0
I	µg	150.0	37.0	6.0	25.0
Se	µg	55.0	0.8	2.0	1.4

* the content of digestible minerals in potato varieties [Food Standards Agency 2007]; Dietary Reference Intakes (DRIs) 2014
**ns – not specified

The contents of Ca, Fe, Zn in tubers were significantly different between *Solanum* species grown under the same conditions [Andre *et al*. 2007]. Among the species, *Solanum gourlay* and *S. microdontum* have the highest content of Ca in tubers, while *S. kurtzianum* and *S. tuberosum* are characterized by the lowest concentration of Ca in tubers under condition of good plant supply with this element [Bamberg *et al*., 1998]. Although the skin is generally more abundant in Ca than pulp [Ereifej *et al*. 1998, Wszelaki *et al*. 2005], differences in Ca contents in tubers dependent on *Solanum* species do not seem to be related to differences between skin and pulp [Bamberg *et al*. 1998]. Andre *et al*. [2007] observed a strong correlation between Ca and Fe concentrations in tubers, while weak yet considerable one between Fe and Zn contents in 74 domestic Andean *Solanum* species.

They noted that some genotypes from *S. ajanhuiri* group had extremely high contents of Ca and Fe in tubers, and that their level explains only about 13% of Fe variation. It was also shown that *S. tuberosum* genotypes cultured under the same conditions differed with nitrogen [Rexen 1976, Sawicka 1991, Mazurczyk & Lis 2001], potassium (K) [Van Marle *et al*. 1994, Sawicka 1991, Ereifej *et al*. 1998, Mazurczyk & Lis 2001, Tekalign and Hammes 2005, Gugała *et al*. 2011], phosphorus (P) [Randhawa *et al*. 1984, Sawicka 1991, Ereifej *et al*. 1998, Mazurczyk & Lis 2001, Trehan & Sharma 2003, Tekalign & Hammes 2005, Gugała *et al*. 2011], sulfur (S) [Tekalign & Hammes 2005, Żołnowski 2013], calcium (Ca) [Randhawa *et al*. 1984, Ereifej *et al*. 1998, Van Marle *et al*. 1994, Sawicka 2000, Tekalign & Hammes 2005, Karlsson *et al*. 2006, Żołnowski 2013], magnesium (Mg) [Randhawa *et al*. 1984, Sawicka, 1991, Ereifej *et al*., 1998, Allison, *et al*. 2001b, Wyszkowski, 2001, Tekalign & Hammes 2005, Sawicka 2016], iron (Fe) [Randhawa *et al*. 1984, Sawicka & Mikos-Bielak 1995, Ereifej *et al*. 1998, USDA 2012, Żołnowski 2013, Sawicka *et al*. 2016], zinc (Zn) [Randhawa *et al*. 1984, Ereifej *et al*. 1998, Tekalign & Hammes 2005, Broadley *et al*. 2007, Żołnowski 2013, Zarzecka *et al*. 2016], copper (Cu) [Randhawa *et al*., 1984, Sawicka, Mikos-Bielak, 1995, Ereifej *et al*., 1998, Tekalign & Hammes 2005, Zarzecka *et al*. 2016], and manganese (Mn) content [USDA 2012, Żołnowski 2013, Zarzecka *et al*. 2016].

Different concentrations of K, Mg, Fe, Zn, Cu, Mn in tubers were also recorded between commercially available potato cultivars [Sawicka & Mikos-Bielak 1995, Casañas Rivero *et al*. 2003, Di Giacomo *et al*. 2007, Zarzecka *et al*. 2016]. It is likely that the content of mineral compounds in potato tubers can be genetically manipulated through the commercial breeding programs [Zimnoch-Guzowska, 2011].

The genotypic variability associated with cultivar features plays a dominant role in the variability of macronutrients in *Solanum tuberosum* tubers. According to Sawicka [1991], the share of phenotypic variability of 34 potato cultivars, tested in two series, was 1.4-36.2% within the overall macronutrients variability (Table 2).

Tabele 2. Impact of varieties and years on the contents of N, P and K and their percentage share in total variation and coefficients of repeatability according to Sawicka [1991]

Series	Element	The coefficient of repeatability	The significance of the impact			The percentage of variance in total variance		
			varieties	years	varieties × years	varieties	years	varieties × years
I	N	0.44	**	**	**	9.8	41.0	47.7
II		0.20	**	**	**	14.3	7.7	77.9
I	K	0.07	**	ns	**	6.5	82.2	1.6
II		0.04	**	**	**	1.4	34.5	56.9
I	P	0.88	**	**	*	36.2	4.9	50.8
II		0.66	ns	**	**	16.8	8.8	73.0

* significant at $p_{0.05}$, ** significant at $p_{0.01}$, ns – insignificant at the level of $p_{0.05}$

I – the first series – the years 1983-1987 (21 varieties); II – second series – the years 1986-1989 (13 varieties)

Cooperation of cultivars with climatic conditions during the study appeared to be the dominant source of variability for nitrogen and phosphorus. Variability coefficients for P and N were 16.5% and 16.7%, respectively with the scatter of results from 8.0% to 25.5% for phosphorus and from 11.8% to 25.8% in the case of nitrogen (Table 2).

Different weather conditions in the study years were recognized as the main reason for the differences in potassium content. The highest repeatability coefficient among tested macronutrients was obtained in the case of phosphorus in both series of tests, which proves the high reproducibility of assessments over the years. In opinion of Seiler and Campbell [2004], Sawicka [1991] as well as Mazurczyk & Lis [2001], the phenotypic variability of potato cultivars, in terms of each characteristic of tuber chemical composition, is a combined effect of genetic and environmental variation. Seiler and Campbell [2004] demonstrated that the amount of variance genotype components, in the case of N, Ca, and K, is high and indicates a potential possibility for improvement of these traits through the selection of cultivars. The share of phenotypic variation for P and Mg is low, which may suggest that the improvement of these traits by means of selection will be difficult.

ENVIRONMENTAL VARIABILITY OF MINERALS IN POTATO TUBERS

Variability of soil and atmospheric environment significantly modifies the level of all macronutrients and microelements in potato tubers. The diversity of the environment in which plants grow, causes, according to Sawicka [1991, 2000, 2016], Mazurczyk & Lis [2001], Seiler and Campbell [2004], modifications in of self-regulation processes, both within the bush, and the crop. It may therefore be a variation within the plant, shrubs, and plant variability associated with the years and localities. Research performed by Seiler & Campbell [2004] showed no effect of weather conditions on the content of potassium and magnesium in tubers. Studies of Sawicka & Mikos-Bielak [1995], Wyszkowski [2001], Zarzecka *et al*. [2006, 2016], Żołnowski [2013], Sawicka [2016] revealed that environmental conditions, particular weather, exert the largest impact on magnesium accumulation in tubers. A high concentration of this element is favored by high rainfall sums and moderate daily air temperatures.

Potato yields in the last 50 years have significantly increased, mainly as a result of the widespread use of pesticides, fertilizers, plant growth regulators, and irrigation. The application of herbicides may contribute to the increase in the content of iron and manganese in tubers [Zarzecka 2004, Gugała & Zarzecka 2011, Zarzecka *et al*. 2006, 2016]. In the opinion Gugała and Zarzecka [2011] the insecticides applied to control the Colorado beetle increased potassium content in potato tubers compared with the control. Moreover the highest phosphorus content was determined in the tubers of potato harvested from the plots sprayed with the insecticides: Regent 200 SC and Calypso 480 SC. Rudzińska-Mękal & Mikos-Bielak [2000] reported the increase in these elements contents due to growth regulators.

The use of mineral fertilizers in potato cultivation generally accelerates the plant growth and improves the tuber yield [Allison *et al*. 2001a, Trehan & Sharma 2003, White *et al*. 2005, Żołnowski 2013]. It is clear that the use of nitrogen (N) increases the content of this element in tubers [Wyszyński 2001, Żołnowski 2013], and applying the phosphorus fertilizers increases the P concentration in tubers [Rocha *et al*. 1997, Trehan & Sharma 2003]. Application of potassium fertilizers causes the increase in K content in tubers [Allison *et al*. 2001b, Żołnowski 2013], while use of calcium or magnesium fertilizers enhances the Ca level [Bamberg *et al*. 1998, Sawicka 2000, Karlsson *et al*. 2006]. Fertilization using magnesium salts also makes Mg content in tubers increased [Allison *et al*. 2001a, Wyszkowski 2001, Żołnowski 2013]. The use of these fertilizers can also have an impact on the content of other minerals in tubers. Although the use of nitrogen fertilizers often has little effect on the tuber, contents of K, Ca, and Mg may lead to some reduction in Fe and P contents in tubers [Allison *et al*. 2001a]. In turn, the use of phosphate fertilizers can raise the levels of N and Mg in tubers, but it may also reduce the content of Mn [Żołnowski 2013]. Application of potassium fertilizers often, but not always, increases the Mg content in tubers, although at the same time reduces the content of Ca and P [Allison *et al*. 2001a, Żołnowski 2013]. The use of calcium fertilizers generally reduces the Mg content; however it can raise the levels of P, S, and K tubers [Żołnowski 2013]. These effects are not only the result of complex interactions between minerals in the soil and consequently uptake by plants, but also the effects within the mineral composition of tissues and redistribution of these elements across the plant. These studies indicate that the content of mineral compounds in tubers depends largely on the phyto-availability of various minerals for plants. Enabling the mineral profiling of tubers can therefore be used to verify the origin of regional products [Casañas Rivero *et al*. 2003, Di Giacomo *et al*. 2007, Żołnowski 2013, Sawicka 2016].

There have been an extensive review of the available literature on the shortage and excess of certain elements in potato plants and the findings were compared with observations carried out under organic and sustainable cultivation systems. It was observed that contents of P, K, Mg, S, Fe, Mn, and Cu are often higher in potatoes grown in the organic system, while N and Mn contents in tubers is higher in potatoes grown conventionally [Wszelaki *et al*. 2005, Sawicka *et al*. 2016]. Complex interactions between mineral compounds in the soil with interactions of minerals and their distribution within the plant indicate that differences in the concentrations of minerals in tubers from contrast cultivation systems are unlikely to be the result of a simple dilution effect due to increased yields.

Other environmental factors that affect the tuber yield are among others: irrigation and elevated CO_2 concentration. Increasing the tuber productivity due to irrigation appears to have negligible influence on the contents of N or K in tubers, but it may increase the P content, while reducing the concentration of Ca and Mg in tubers [Sawicka & Mikos-Bielak 1995]. In opinion of Fangmeier *et al*. [2002], increasing the efficiency of potato due to elevated CO_2 concentration led to a reduction in the concentrations of N, K, and Mg in mature tubers. These studies suggest that increased tuber yield may be associated with decreased levels of certain, but not all, minerals in tubers.

Contents of minerals in potato tubers also differ greatly depending on the cultivation locality [Sawicka & Mikos-Bielak 1995, Mazurczyk & Lis 2001, Zarzecka *et al*. 2006, Sawicka 2016].

THE CONTENT OF MINERAL COMPOUNDS IN TUBERS OF HIGHLY PRODUCTIVE GENOTYPES

There are evidences that highly producible potato genotypes are characterized by a lower mineral content in tubers than genotypes with lower fertility, when grown in the same environment (Table 3). For example, comparative studies involving a small number of genotypes have shown that potassium (K) [Tekalign & Hammes 2005, Żołnowski 2013, Tian *et al*. 2016], phosphorus (P) [Randhawa *et al*. 1984, Tekalign & Hammes 2005, Trehan & Sharma 2003, Żołnowski 2013, Tian *et al*. 2016], sulfur (S) [Tekalign & Hammes 2005], calcium (Ca) [Randhawa *et al*. 1984, Sawicka 2000, Tekalign & Hammes 2005], magnesium (Mg) [Allison *et al*. 2001a, Sawicka 2000, Tekalign & Hammes 2005, Zarzecka *et al*. 2006, Żołnowski 2013, Tian *et al*. 2016], iron (Fe) [Randhawa *et al*. 1984, Tekalign & Hammes 2005], zinc (Zn) [Tekalign & Hammes 2005], copper (Cu) [Tekalign & Hammes 2005, Zarzecka *et al*. 2016], and manganese (Mn) [Tekalign & Hammes 2005, Zarzecka *et al*. 2016] contents in potato tubers were lower at high producible cultivars than those with lower fertility grown in the same experiment, but none of these dependencies was statistically verified. Moreover, Randhawa *et al*. [1984] found insignificant positive correlations between tuber yields vs. contents of K, Mg, Zn, and Cu in fresh matter of tubers.

Table 3. Variation in tuber mineral contents among *Solanum* genotypes in diverse trial*

Element	Genotypes	Abundance (*n*)	Trial	Contents Mean (±S)	References
N	*S. tuberosum varieties*	33	Field, low N	13.2 ±2.1	Rexen 1976
N	*S. tuberosum varieties*	33	Field, high N	15.8±2.6	Rexen 1976
N	*S. tuberosum varieties*	27	Field	11.2±1.8	Mazurczyk, Lis 2001
P	*S. tuberosum varieties*	10	Field	2.32±0.65	Ereifej *et al*. 1998
P	*S. tuberosum varieties*	3	Glasshouse	2.97±0.45	Trehan, Sharma 2003
P	*S. tuberosum varieties*	4	Field	2.85±0.38	Tekaling Hammes 2005
K	*S. tuberosum varieties*	10	Field	13.8±1.7	Ereifej *et al*. 1998
K	*S. tuberosum varities*	4	Field	24.9±3.5	Tekaling, Hammes 2005
K	*S. tuberosum varieties*	26	Field	21.3±1.5	Mazurczyk, Lis 2001
S	*S. tuberosum varieties*	4	Field	2.38±1.84	Tekalign, Hammes 2005
S	*S. tuberosum varieties*	26	Field	0.45±0.14	Randhava *et al*. 1984
Ca	*Solanum sp.*	21	Glasshouse, law Ca	1.52±0.47	Randhawa *et al*. 1984
Ca	*Solanum sp.*	21	Glasshouse, high Ca	0.50±0.17	Allison *et al*. 2001a
Ca	*Andean landraces*	74	Field	1.34±0.13	Tekalign, Hammes 2005
Mg	*S. tuberosum varieties*	10	Field	0.98±0.08	Sawicka, Mikos-Bielak 1995
Mg	*S. tuberosum varieties*	2	Field	1.38±0.14	Ereifej *et al*. 1998
Mg	*S. tuberosum varieties*	4	Field	55.9±12.1	Allison *et al*. 2001a
Mg	*S. tuberosum varieties*	26	Field, 4 rates N	11.3±7.8	Tekalign, Hammes 2005
Fe	*Andean landraces*	74	Field	20.4+/-4.2	Andre *et al*. 2007
Zn	*Andean landraces*	74	Field	14.6±6.85	Andre *et al*. 2007
Cu	*S. tuberosum varieties*	10	Field	7.80±1.40	Ereifej *et al*. 1998
Mn	*S. tuberosum varieties*	10	Field		Ereifej *et al*. 1998

* each trial comprised *n* genotypes grown under identical conditions. Tubers contents of N, K, S, Ca and Mg are given in $g·kg^{-1}$ dry matter. Tuber contents of Fe, Zn, Cu and Mn are given in $mg·kg^{-1}$ dry matter

Relationships between the mineral content in the tubers and tuber yield in *n Solanum tuberosum* genotypes of different earliness groups are presented in Table 4. Extensive studies upon genetic variability referring to the mineral content in potato tubers were initiated by Crop Research Institute in Scotland. Samples from field experiments, including 26 potato cultivars, served to support the hypothesis that the cultivars with higher fertility have lower mineral content in tubers than those with lower fertility. However, these studies did not confirm significant dependencies between fresh tuber matter and contents of N, K, S, Ca, Mg, Fe, Zn, or Mn in tubers, and content of P ($p = 0.014$) and Cu concentration ($p < 0.001$) increased considerably along with the increase in the fresh matter tubers grown. Gembarzewski [2000] reported that at high potato yields, contents of iron, manganese, and copper were diminished. According to WHO recommendations, a man should intake 10-18 mg Fe and 2.5-6.0 mg Mn in daily diet [2015].

Table 4. Relationships between the contents of mineral elements in tubers and tuber yield among *N* genotypes of *Solanum tuberosum* in diverse trials

Element	Gradient	Intercept	Number *n*	R^2	P	Units (*y/x*)	References
N	-3.59±2.48 E-0.5	13.5±1.62	26	0.000	0.161	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Allice *et al*. 2001a
K	6.80±6.10 E-0.2	29.7±11.4	8	0.171	0.308	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Mazurczyk, Lis 2001
K	-3.37±1.93 E-0.4	36.5±6.84	4	0.603	0.223	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005
P	-1.66±0.87 E-0.5	0.70±0.16	27	0.380	0.104	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Mazurczyk, Lis 2001
P	-1.37±0.48 E-03	4.44±0.53	3	0.890	0.215	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al*. 1984
S	-2.13±0.57 E-0.5	9.75±2.01	8	0.875	0.065	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005
S	0.53±1.84 E-0.6	1.11±0.12	8	0.003	0.777	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling & Hammes 2005
Ca	-1.13±1.54 E-0.3	0.45±0.29	26	0.082	0.479	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al*. 1984
Ca	-6.57±4.78 E-0.6	0.84±0.17	4	0.485	0.303	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005
Ca	-0.69±01.27 E-0.6	0.43±0.08	4	0.012	0.584	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Allice *et al*. 2001a
Ca	0.35±4.66E-04	0.16±0,09	26	0.012	0.594	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al* 1984
Mg	-1.42±0.43E-05	1.17±0,06	8	0.001	0.943	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Allice *et al*. 2001b
Mg	-1.24±0.89E-05	1.81±0,31	3	0.915	0.189	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005
Mg	-0.56±1.58E-06	1.07±0.10	25	0.492	0.299	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Sawicka, Mikos-Bielak 1995
Mg	-1.99±3.40 E-0.2	10.1±6.33	26	0.005	0.727	($g \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al*. 1984
Fe	0.44±4.67 E-0.2	5.27±869	8	0.054	0.580	($mg \cdot kg \cdot DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al* 1984, Sawicka 2016
Zn	5.75±6.76 E-02	-4,52±12.6	8	0.001	0.928	($mg \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005
Cu	-3.09±E-0.50	4.85±1.55	8	0.108	0.427	($mg \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Randhava *et al*. 1984
Mn			4	0.199	0.554	($mg \cdot kg^{-1} DM \cdot kg^{-1} FW \cdot ha^{-1}$)	Tekaling, Hammes 2005

* linear relationship ($y = bx + c$) was assumed between the concentration of a mineral element in the tuber (y) and tuber yield (x), and sees on gradients (b) and intercepts (c), correlation coefficients (R^2) and probability that the gradients is zero (p) were calculated

Consuming 200 g potato may cover daily iron requirements in about 15%. Contents of minerals in edible potato cultivars was significantly positively correlated with their efficiency suggesting that breeding works are capable of enhancing the potato tuber yield per an area unit. According to Zimnoch-Guzowska [2011], increasing the minerals concentration in potato tubers is possible due to biotechnological methods application.

FLUCTUATIONS IN MINERAL CONTENT IN FOOD PRODUCTS

For the first time, Mayer [1997] drew attention to the possible decrease in dry matter content and the concentrations of Ca, Cu, Mg, and Na in raw vegetables as well as contents of Cu, Fe, K, and Mg in fresh fruits available in the UK between 1930 and 1980. Then, White & Broadley [2005], have shown that the mineral content in the dry matter of British food products, which is the basis to offset the effects of tissues hydration, confirmed that the average contents of Cu, Mg, and Na in dry matter of vegetables, and mean concentrations of Cu, Fe, and K in dry matter of fruits available in the UK, declined significantly between 1930 and 1980. White & Broadley [2005] also analyzed the comparable data from the United States, and found that the average contents of Ca, Cu, and Fe in dry matter of vegetables and average contents of Cu, Fe, and K in dry matter of fruits decreased significantly since the 1930s. Both publications have used appropriate statistical tests. At the same time, Davis *et al*. [2004], using the median and quantile along with other statistical tests, have concluded that contents of Ca, Fe, and P in vegetables declined significantly between 1950 and 1999. Davis [2006] also noted that the contents of Cu and Na in the dry matter of fruits and vegetables in the UK decreased significantly between 1930 and 1980. However, the observation that similar changes in the geometric mean and median for mineral content occurred in the potato tubers, as well as in vegetables, both in the United Kingdom and the United States, results in similar importance for the consumer. This suggests that this phenomenon may be a consequence of the adoption of modern cultivars and/or agricultural practices [White, Broadley 2005, Sawicka *et al*. 2016]. Unfortunately, none of these studies have not provided sufficient evidence to determine whether the concentration of mineral compounds of a single vegetable or fruit does not change significantly over time, either in Great Britain or the United States. In the end, different cultivars and/or cultivation technologies or cropping systems should be directly compared under the same environmental conditions to determine whether the content of minerals results from changing cultivars or agricultural practices [Broadley *et al*. 2006, Davis *et al*. 2004, Davis 2006, Zarzecka *et al*. 2006, Żołnowski 2013, Sawicka 2000, Sawicka *et al*. 2016].

It is believed that the increase in the potato tubers yield per unit area causes a reduction in the mineral content in the production due to the effect of "dilution" resulting from the plant growth rate exceeding the ability of plants to accumulate these elements [Gembarzewski 2000], which are the effects of variable factors, both of environmental and genetic nature [Sawicka & Mikos-Bielak 1995, Davis *et al*. 2004, Davis 2005, Sawicka 2016]. It has long been obvious that acceleration of plant growth rate and change in environmental factors such as temperature, light intensity, irrigation, fertilization, and application of pesticides, tend to reduce the concentration of macronutrients in plant tissues [Zarzecka 2004, Żołnowski 2013, Sawicka 2016]. Numerous recent studies have shown that the content of various minerals is below in genotypes with higher fertility [Sawicka 1991, 2000, Gembarzewski 2000, Davis *et al*. 2004, Garvin *et al*. 2006, Sawicka *et al*. 2016]. Garvin *et al*. [2006] observed negative dependence between contents of Fe, Zn vs. Se concentration in yield, both in the laboratory and in the field.

Ion relations

Not only the general content of macronutrients and microelements, but also proportions, in which they are present in plant products, are important indicators determining the quality of potato tubers [Wyszkowski 2001, Zarzecka *et al*. 2006, Żołnowski 2013, Sawicka 2016]. Improperly balanced plant nutrition translates into ion ratios in the food, and these are usually highly significantly correlated with the soil abundance. Nutrient uptake by plants depends on their concentrations in the soil and on such phenomena as synergism and antagonism, which directly affect the outcome, i.e. the chemical composition of plants. The antagonism between uptake of individual minerals from tubers by human and animal causes that not only chemical composition is important but also the mutual relationships between various elements. The relative proportions of minerals in tubers are dependent on their contents and the atomic mass. The most important, for nutritional reasons, the potassium to calcium and magnesium ratio proved to be too high in most of examined potato samples of [Wyszkowski 2001, Żołnowski 2013, Sawicka *et al*. 2016]. Excessive potassium concentration in dry matter is unable to balance neither the deficiency of calcium nor the optimum magnesium content. The calcium to magnesium ratio frequently appears to be improper. This is dangerous for human and animal health, as these elements are taken up by organisms not only in the needed but luxurious amounts. Sawicka [2016] found that changes in the ratio between K, Ca, and Mg are dependent on the cultivation system. According to Wyszkowski [2001], magnesium fertilization positively influences on the value of Ca : P, Ca : Mg, K : Mg, and K : (Ca + Mg) ratios causing nutritionally preferred narrowing during the phase of technological maturity at all crop species and at each of their developmental stage. Recommendations for agricultural practice should therefore take into account the level of fertilization in the production fields, based on a diagnostic analysis of soil and plants.

Analysis of the chemical composition of crops may indicate the ingredients to which a special attention should be paid during fertilization. The ion relations usually refer to crops intended for animal feed [Gembarzewski 2000, Wyszkowski 2001, Sawicka 2016]. The optimum values of particular element ratios expressed in milligram-equivalents amount to: K : (Ca + Mg) = 1.6-2.2 : 1, K : Mg = 6 : 1, K : Ca = 2 : 1, K : Na = 5-10 : 1, Ca : Mg = 2-3:1, K : Ca = 2 : 1 as well as molar ratio Ca : P = 2 : 1 [Żołnowski 2013].

Equivalent Ca:Mg ratio providing mutual relations between divalent ions in different storage organs of plants is dependent on the NPK fertilization and a cultivar. Under the impact of increasing NPK doses, calcium share relative to magnesium increased in tubers, on average, from 0.51 : 1 for the control object to 0.68 : 1 in objects fertilized with the highest NPK rate ($N_{160}P_{104}K_{200}$). Increasing nitrogen or potassium nutrition, in opinion of Wyszkowski [2001] and Żołnowski [2013], does not significantly affect the formation of a Ca : Mg ratio in potato tubers. It is noted, however, some tendency to increase in the proportion of calcium to magnesium ratio in the dry matter of tubers due to applied fertilizer (r = 0.81**).

Equivalent K : (Ca + Mg) ratio is one of the most important parameters characterizing the ionic balance in the storage organs of crops. In the diet, it should be at the level of 1.6-2.2 : 1. Żołnowski [2013] did not find this value diversity within different cultivars of the same species. He did not either show a significant effect of NPK and N fertilization on K : (Ca + Mg) ratio.

Equivalent K : Mg ratio, nutritionally important, and depending both on the species and cultivar [Żołnowski 2013, Sawicka 2016]. This ratio, in studies performed by Żołnowski [2013] was significantly correlated with NPK nutrition (r = 0.73** – r = 0.96**), however he could not present statistical evidence for fertilization-determined differences. Study by Wyszkowski [2001] revealed that the K : Mg ratio value in potato tubers under the influence of potassium fertilization got broadened. In opinion of Żołnowski [2013], relationship between potassium dose and K : Mg ratio K : Mg (r = 0.96**) is the result of a systematic decrease in the magnesium content under the influence of fertilizer used, as well as the increase in potassium content.

Equivalent K:Ca ratio. In recent years, a further extension of this relationship in agricultural crops can be observed, which is associated with increased calcium deficiency in soils. The situation is exacerbated by the fact of less and less use of manure in crop production. This fertilizer is an important source of calcium for soils and plants. The ratio of K : Ca in the food should be at a level of 2 : 1 [Wyszkowski 2001]. Value of this ratio depends on NPK nutrition. Under the influence of potassium fertilization, the K : Ca ratio gets broadened from 12.44 to 17.33 : 1. The K : Ca value in potato tubers is primarily dependent on the cultivar [Żołnowski, 2013].

Sawicka [2016], when examining the ion relations in potato tubers, found that K : Ca; K : (Ca + Mg) as well as Ca : Mg and K:Mg ratios remarkably deviate from assumed optimum. Mutual proportions K : (Ca + Mg), K : Ca, K : Mg are above, while Ca : Mg below optimum ratios for these elements. Only the Ca : P was optimum.

CONCLUSIONS

The concentration of minerals in potato tubers depends both on environmental and genetic factors. One of the most important environmental factors is the phyto-availability of minerals in the soil. Some results confirm the hypothesis that an increase in tuber yield, either by increasing the CO_2 concentration or by breeding the cultivars with higher specific productivity, can lead to reduced levels of certain minerals in tubers, but it is not widely recognized. The decrease in mineral content in potato tubers can be prevented by means of appropriate application of mineral fertilizers. Increasing the efficiency of yield through the use of mineral fertilizers exerts different effects on mineral content in tubers, depending on the fertilizer composition, soil type, and crop genotype. Interactions between minerals in the soil and in fertilizer, can affect the mineral content in tubers, regardless of the "diluting" phenomenon. Therefore, it should be possible to increase the concentration of minerals in tubers by combining the genotypes that have naturally higher mineral concentrations in tubers with corresponding fertilization strategies in order to achieve the most essential minerals in the diet, without compromising the high yield (efficiency) of crop plants. The mineral nutritional status has a significant impact on the health of humans and animals. Use of high-mineral fertilizers, especially nitrogen, can contribute to a reduction in the mineral content in potato tubers. In practice, mineral malnutrition can be solved through supplementation, food enrichment, well-designed diets, diversification, and/or increasing the concentration of minerals in edible crops. Bio-strengthening the plant by the use of mineral fertilizers in combination with breeding the cultivars with increased ability to uptake minerals is recommended as a trial for immediate agronomic strategy, both to increase the concentration of minerals in food products and to improve the efficiency of crops on barren soils.

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ZMIENNOŚĆ GENOTYPOWA I ŚRODOWISKOWA PIERWIASTKÓW W BULWACH ZIEMNIAKA
ARTYKUŁ PRZEGLĄDOWY

Streszczenie Na podstawie literatury przeprowadzono analizę zakresu zmienności genetycznej związanej ze stężeniem składników mineralnych w bulwach ziemniaka. Opisano skutki stosowania nawozów mineralnych na zawartość składników mineralnych oraz wzajemne stosunki tych pierwiastków w bulwach ziemniaka. Przeanalizowano zakres zmienności fenotypowej, determinowanej zmiennością genetyczną i środowiskową. Sprawdzano też hipotezę, że większe plony, wygenerowane albo przez aplikację nawozów mineralnych i/lub stosowanie odmian o wyższej plenności mogą doprowadzić do obniżenia stężenia składników mineralnych w bulwach ziemniaka.

Słowa kluczowe: czynniki biotyczne, genotypy *Solanum*, makropierwiastki, mikropierwiastki, stosunki jonowe, zmienność

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