Original article

Effects of foliar fertilization with potassium and micronutrients on potato yield and quality

R. Gaj and J. Borowski-Beszta

Poznan University of Life Sciences, Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznań, Poland

Summary

The research was carried out over the period 2014–2016, on light soils, at a farm located in western Poland. The aim of the study was to determine the effect of foliar fertilization with potassium sulfate (SOP) and micronutrients (Zn, Cu, Mn, B) on potato yields and selected quality parameters of tubers (protein, starch, dry matter). The subject of the study were potato varieties Hermes and Zorba, cultivated for the production of crisps and French fries, respectively. Consistent with the adopted experimental setup (randomized block design, 4 replications for each variety), the following treatments were analyzed: (i) SOP foliar application (twice, in total: 8.6 kg K ha⁻¹); (ii) micronutrient foliar application (twice, in total: 12 g Zn ha⁻¹, 12 g Cu ha⁻¹, 300 g Mn ha⁻¹, 500 g B ha⁻¹); (iii) SOP plus micronutrient foliar application (i) + (ii) and the control (no foliar treatment). Regardless of the analyzed experimental variant, higher tuber yields were obtained in 'Hermes' variety, and these ranged from 45 t ha⁻¹ to 71 t ha⁻¹, depending on the study year. When compared to the control, the largest increases in 'Hermes' yields and tuber protein contents (24% and 6%, respectively) were observed in 2014 – as a result of foliar fertilization with SOP (i). In the whole observation period, 'Zorba' yields ranged from 32 t ha⁻¹ to 65 t ha⁻¹. In 2016, this variety showed a positive response to foliar fertilization with micronutrients (ii). In comparison to control, 'Zorba' yields and tuber protein contents increased by 15% and 21%, respectively.

Keywords

dry matter, foliar potassium fertilization, potato varieties, protein, starch

Introduction

Potato yield, its quality and tuber chemical composition depend on a number of environmental and agronomic factors, among which the most important are: water supply, genetic yield potential of a given variety, climatic conditions during the growing period (precipitation distribution), soil conditions, and agro-technical solutions (e.g. mineral and organic fertilization) (Bienia et al., 2018; Gaj et al., 2018; Tilman et al., 2011; Daccache et al., 2011; Rębarz et al., 2015). In the group of agronomic factors, the level of fertilization with macro- and micronutrients, effectiveness of disease and pest control and relevance of cultivation treatments are of key importance (Erisman et al., 2008). An important element of

Significance of this study

What is already known on this subject?

- Potato belongs to the group of plants positively responding to potassium application to the soil. Foliar application of nutrients is an important crop management strategy in maximizing crop yields.

What are the new findings?

- A lack of studies which examine the effect of in-season foliar application of potassium combined with micronutrient addition on tuber yield and quality. Response to foliar sprays is often variable and not reproducible due to the existing lack of knowledge of many factors related to the penetration of the leaf-applied solution.

What is the expected impact on horticulture?

- To contribute to improving potato yield and tuber quality.

modern technology of potato production is optimal mineral fertilization that takes into account various requirements of potato varieties, soil fertility and use form (AbdelGadir et al., 2003). The main goal of potato producers is to provide raw material suitable for further processing. Both, the environmental and agronomic factors (e.g., fertilization technique) can significantly modify tuber technological features, such as dry matter or starch contents (Lutomirska, 2008; Kumar et al., 2007; Lal, 1983). As a plant species having a particularly high nutrition demand with regard to potassium (Panique et al., 1997), potato requires K-rich sites. Regmi et al. (2002) suggested that inadequate K nutrition leads to ever increasing soil K imbalance in agricultural ecosystems and to yield stagnation. Potassium has many different roles in plants, and those associated with plant water management and sugar synthesis are of particular importance (Marschner, 2012; White and Karley, 2010; Amtmann et al., 2006). According to Blagoeva et al. (2004), potatoes are K-preferring crops because they absorb 1.5-fold more K than nitrogen and 4-fold more K than phosphorus. Potato tubers are rich in starch, whose synthesis is associated with a high demand for potassium and magnesium. The role of potassium is far and wide acknowledged in potato fertilization technologies which mainly focus on issues concerning K fertilizer forms and doses applied before planting (Davenport and Bentley, 2001), and address the effect of potassium on enhancing plant resistance to pathogens (Lambert et al., 2005; Blachinski et al., 1996; Barraclough and Haynes, 1996; Wang et al., 2013).

Essential plant nutrients (K, P, Mg) are mainly applied to soil and plant foliage (micronutrient) for achieving maximum economic yields. Soil application method is more common and most effective for nutrients, which are required in higher amounts (Fageria et al., 2009). Improvement of the effectiveness of fertilizer components depends, inter alia, upon their dose and the method of application (Czyżyk, 2011). The basic criterion for the effectiveness of foliar fertilization is nutrient uptake rate and nutrient ability to move within the plant (Kocoń, 2016). Foliar fertilization requires higher leaf area index for absorbing applied nutrient solution in sufficient amount; it may be necessary to have more than one application, depending on severity of nutrient deficiency (Fageria et al., 2009). The advantage of foliar fertilization is the speed of action and high effectiveness of micronutrients used in small amounts (Blachiński et al., 1996; Szewczuk and Michałojć, 2003). In terms of nutrient absorption, foliar fertilization can be from 8 to 20 times as efficient as ground application (Girma et al., 2007). In the critical stages of plant growth, nutrient uptake is very intensive, and conventional soil fertilization does not always guarantee appropriate availability of nutrients to plants. Hence, crop response occurs in short time in foliar application compared to soil application (Fageria et al., 2009). However, this efficiency is not always achieved in actual practice. The potato's high demand for nutrients starts in the period of tuberization (formation of tubers on underground stolons), and depends on the potato variety being grown (Trawczyński, 2003). The chemical composition of tubers is a basic determinant of their use, which sets specific requirements as to the quality of tubers both in terms of external features (shape, size) and those internal, which define potato eating quality, shelf-life, or type of industrial processing. Among quality parameters, the content of protein and starch is of particular importance. The true protein, despite its relatively low content in tubers, constitutes a valuable source of basic amino acids for humans and animals (De Jong, 2016; Woolf, 1987).

Starch is the main polysaccharide in tubers with a content ranging from 15% to 18%. The starch content plays a key role in the usefulness of potato tubers for processing and gastronomy. In addition, it is broken down into glucose, which is the basic source of energy indispensable for functioning of the human body (Pobereżny et al., 2011). The influence of micronutrient fertilizers on the quality of tubers has been up to now poorly understood (Boliłłowa, 2003; Kozera and Barczak, 2007).

The present study was based on a working hypothesis that foliar fertilization with potassium sulfate (SOP) and micronutrients would increase tuber yields as well as improve quality parameters. The aim of the present study was to assess the effects of foliar fertilization with potassium sulfate and micronutrients applied as chelates on potato tuber yield and quality parameters.

Materials and methods

The study was carried out in the years 2014–2016, at the Jagrol farm, situated in Pierzchno, Wielkopolska, 52°14'51"N, 17°05'22"E. Two varieties of potato cultivated for different purposes were analyzed: 'Zorba' (French fries) and 'Hermes' (crisps).

The experiment was set on light soils, of the IVb quality class. Soil characteristics of the fields for each year are presented in Table 1. The content of available nutrients, measured each year before fertilizer application into the top-soil, was high/very high for phosphorus (74–100 mg P kg⁻¹ soil), medium for potassium [125–174 mg K kg⁻¹ soil, assessed with the Egner-Riehm-method (Egner et al., 1960)], high for magnesium (61–80.6 mg Mg kg⁻¹ soil, assessed with the Schachtschabel (1955) method. The amount of mineral N (N_{min}) was 75–148 kg ha⁻¹ (0.01M CaCl₂). The amount of soil organic carbon was determined using a Vario-Max analyzer. Each year, before the start of the experiment, the fields were planted with winter cereals. Cattle manure at a dose of 20 t ha⁻¹ was applied in the fall to all experimental plots. Crop residues from winter wheat and manure were incorporated into the soil by ploughing at 20 cm depth.

The single factor experiments were set in a randomized complete block design. Four experimental variants were analyzed for each potato variety in four replications, including: (i) two-time foliar supply of potassium sulfate SOP; (ii) two-time foliar supply of micronutrients; (iii) (i+ii) SOP + micronutrients foliar supply; and (iv) no foliar treatment (control). Consistently with the experimental design, foliar fertilization with potassium and microelements was performed twice during the growing season. The first foliar application of potassium as SOP (K₂SO₄ – 45% K and 18.4% S) and micronutrients was performed during tuber initiation (BBCH 40), and the second – two weeks later. Micronutrients were applied as chelates (boron as disodium tetraborate). The total supply during two-time foliar treatments was 8.6 kg K ha⁻¹ and 12 g Zn ha⁻¹; 12 g Cu ha⁻¹; 300 g Mn ha⁻¹ and 500 g B ha⁻¹ (Table 2). Foliar treatments with potassium (SOP) and micronutrients (Micro) were carried out on potato plants growing on the soil also fertilized with nitrogen, phosphorus and potassium (NPK). Rates of mineral fertilizers and crop management details are described in Table 2.

Nitrogen was applied into the soil in the spring, immediately before tuber planting, in a two-rate system, using different N forms, i.e.: (1) ammonium phosphate and (2) a solution of urea and ammonium nitrate in water + sulfur UAN+S (26% N + 3% S). In the fall, fertilization with one dose of phosphorus and potassium was carried out at the site designated for cultivation of 'Zorba' variety (French fries), whereas in the case of 'Hermes' variety (crisps), potassium was applied in a divided dose (one in the fall and one in the spring). Phosphorus was introduced into the soil as diammonium phosphate (DAP, 18% N: 20% P). Potassium was applied as K-chlorine (33.2% K).

TABLE 1. Basic chemical properties of the soil used for the study.

Variety	Year	Corg (g kg ⁻¹)	N min (kg ha ⁻¹)	P available (mg P kg ⁻¹)	K available (mg K kg ⁻¹)	Mg available (mg Mg kg ⁻¹)	pH 1M KCl
Zorba	2014	5.90	75	82.84	174.3	80.6	6.5
	2015	6.77	85	95.92	182.6	77.7	6.3
	2016	6.85	148	74.12	141.1	61.2	6.6
Hermes	2014	6.28	80	78.48	166.0	70.2	6.7
	2015	7.15	92	100.3	157.7	69.5	7.1
	2016	6.93	76	96	125.0	80.2	7.2

TABLE 2. Crop management characteristics.

Crop management	Years					
	2014		2015		2016	
	Zorba	Hermes	Zorba	Hermes	Zorba	Hermes
Planting date	06.04	07.04	04.04	04.04	10.04	10.04
Harvest date	20.07	28.08	19.07	24.08	16.07	01.09
Amount of fertilizers (kg ha ⁻¹)						
N	200	160	175	160	144	170
P as DAP	40	30	32	30	30	30
K basal fertilization (KCl)	133	166	114	163	132	193
K foliar application	First treatment: 10 kg SOP, 4.3 kg K ha ⁻¹ Second treatment: 10 kg SOP, 4.3 kg K ha ⁻¹					
Micronutrients application	First treatment: Zn: 6 g ha ⁻¹ , Cu: 6 g ha ⁻¹ , Mn: 150 g ha ⁻¹ , B: 250 g ha ⁻¹ Second treatment: Zn: 6 g ha ⁻¹ , Cu: 6 g ha ⁻¹ , Mn: 150 g ha ⁻¹ , B: 250 g ha ⁻¹					

TABLE 3. Precipitation and temperature in the period of potato growing in 2014–2016 and the averages for long-term period (1991–2015).

Years	Months					
	April	May	June	July	August	April–August
Temperature (°C)						
2014	10.9	10.8	16.7	22.1	18.3	15.76
2015	8.8	13.6	16.1	19.7	22.5	16.14
2016	8.8	15.6	18.6	19.2	18.1	16.06
1991–2015	8.3	13.9	16.9	18.8	18.2	15.22
Rainfall (mm)						
2014	37.8	68.5	16.8	39.4	37.8	200.3
2015	35.8	19.6	73.4	67.2	16	212.0
2016	42.2	38.6	82	154.6	38.4	355.8
1991–2015	29.0	61.2	58.8	87.8	65	301.8

The plantation was irrigated at the time of the study. Total quantities of irrigation water applied in study years were: ‘Hermes’: 750, 700, 500 m³ ha⁻¹; ‘Zorba’: 1,150, 250, 500 m³ ha⁻¹. Meteorological conditions varied over the study period (Table 3). To compare the level and distribution of precipitation and temperatures, the data from the study year were juxtaposed with those from the years 1991–2015.

Both potato varieties were planted in the second week of April, and ‘Zorba’ was harvested in the third week of July, while ‘Hermes’ during the last week of August. Each plot consisted of 6 × 12 m-long rows, with the central two rows designed as harvest. The distance between the rows was 90 cm and plants were spaced at 30 cm. The surface area of the sampling plots was kept at 12 m² (1.8 m × 6.66 m). Potato tubers were harvested by hand. The yield structure was determined based on a sample of 15 kg tubers collected from each plot. For both tested potato varieties, four fractions of tubers were identified with the following crosswise diameter classes in the total yield: <35 mm, 35–45 mm, 45–60 mm, and >60 mm.

Five kg of randomly selected tubers were used for estimating the processing quality attributes, including: the dry matter content using the dry-weight method and the starch content, using the Reiman-Parow scale. Additionally, in each experimental treatment, five tubers were sampled; the samples were cut into small pieces and dried at 105°C, then ground and analyzed for the content of nitrogen. The level of nitrogen in plant tissues was determined using the Kjeldahl

method (Kjeltec 2200 FOSS auto-analyzer). The protein content was calculated based on the obtained values which were multiplied by the coefficient 6.25.

All results were statistically tested using one-way analysis of variance. Since the experimental potato varieties varied with regard to the length of growing period and the way of tuber use, the varieties were not treated as an experimental factor. The mean values of the analyzed variables (yield, dry mass, and starch content) in the tested treatments were compared separately, using one-way ANOVA with the Tukey’s test ($\alpha = 0.05$).

Results and discussion

Tuber yield

The yield and quality of potato tubers can be modified by many factors, of which potassium fertilization is particularly vital. In the present study, in-season foliar fertilization with potassium and micronutrients significantly differentiated tuber yield and quality in the potato varieties tested (Tables 4 and 5). Depending on the variety tested, tuber yields ranged from 45 t ha⁻¹ to 71 t ha⁻¹. This result indicated a high natural productivity of the soil under study. In Poland, the average potato yield ranges from 23.3 t ha⁻¹ to 28.6 t ha⁻¹ (GUS, 2019). The main reason behind low potato yields achieved at the country level and the lack of yield stabilization is the environmental and nutritional stress that negatively affects the formation of basic crop structure components. In the

TABLE 4. Effect of foliar fertilization with potassium and micronutrients on tuber yield, protein content, starch, dry mass and tuber sizes in variety Hermes at the stage of the technological maturity.

Year	Treatment	Total tuber yield (t ha ⁻¹)	Starch (g)	Dry matter (%)	Protein (g kg ⁻¹)	Percentage of tuber sizes (% of total tuber yield)			
						< 35 mm	35–45 mm	45–60 mm	> 60 mm
2014	Control	45.53c*	149.5a	20.70a	107.63a	0.75a	5.10a	31.49a	63.84a
	SOP	56.08a	141.1ab	19.86ab	116.8a	0.62ab	6.17a	36.31a	56.91a
	SOP + Micro	52.59b	127.8b	18.53b	109.1a	0.31b	5.56a	37.02a	56.85a
	Micro	53.97ab	146.5a	20.40a	116.8a	0.31b	4.88a	31.55a	64.53a
2015	Control	51.65a	159.8a	21.73a	113.4a	0.90a	2.11a	22.55a	73.83b
	SOP	54.01a	154.5a	21.20a	104.7a	1.18a	2.55a	11.88b	84.21a
	SOP + Micro	49.35a	151.2a	20.87a	103.4a	0.70a	1.31a	15.56b	82.20a
	Micro	53.01a	154.0a	21.15a	105.3a	0.61a	2.26a	10.85b	86.66a
2016	Control	66.22a	146.0b	20.35b	88.69a	1.21a	4.01a	13.84a	77.29a
	SOP	67.63a	164.5a	22.20a	77.96a	1.25a	3.51ab	16.48a	78.87a
	SOP + Micro	69.24a	166.5a	22.40a	82.79a	0.82ab	2.83ab	13.84a	80.41a
	Micro	71.17a	167.0a	22.45a	87.06a	0.48a	1.87b	14.12a	83.62a

* Values in the same column followed by the same letter are not significantly different, Tukey's test ($P < 0.05$).

TABLE 5. Effect of foliar fertilization with potassium and micronutrients on tuber yield, protein content, starch, dry mass and tuber sizes in variety Zorba at the stage of the technological maturity.

Year	Treatment	Total tuber yield (t ha ⁻¹)	Starch (g)	Dry matter (%)	Protein (g kg ⁻¹)	Percentage of tuber sizes (% of total tuber yield)			
						< 35 mm	35–45 mm	45–60 mm	> 60 mm
2014	Control	51.64a*	136.5a	19.40a	94.57a	0.67a	6.45b	39.71b	51.60a
	SOP	42.20b	107.5b	16.50b	92.28ab	2.11a	7.73ab	43.60ab	43.48ab
	SOP + Micro	48.60ab	134.5a	19.20a	79.4ab	1.08a	11.24a	52.28ab	36.06ab
	Micro	45.09b	112.5b	17.01b	71.71b	0.60a	11.28a	55.66a	32.97b
2015	Control	39.90a	136.5a	19.40a	99.12a	1.21a	5.37ab	36.43ab	55.66a
	SOP	36.68a	107.5b	16.50b	90.58a	1.23a	5.03b	31.37b	58.62a
	SOP + Micro	33.05a	134.5a	19.20a	95.51a	0.79a	6.91ab	37.52ab	55.16a
	Micro	32.98a	112.5b	17.01b	99.50a	0.78a	7.28a	41.00a	50.26a
2016	Control	57.06ab	126.0a	18.35a	73.61a	1.74a	4.31a	33.14a	59.73b
	SOP	54.97b	135.0a	19.25a	86.11a	0.36b	2.35a	19.14b	73.76a
	SOP + Micro	58.51ab	136.0a	19.35a	75.51a	0.50b	2.59a	22.75ab	74.25a
	Micro	65.80a	138.0a	19.50a	89.58a	0.95ab	3.26a	26.34ab	67.55ab

* Values in the same column followed by the same letter are not significantly different, Tukey's test ($P < 0.05$).

major part of Poland, the average potential reduction in potato yields is 10–12% because of insufficient soil moisture (Koźmiński and Michalska, 2001). The main purpose of the currently used potato cultivation technologies is to obtain stable and high quality crops corresponding to market quality standards in a given production direction (Gruczek, 2004). The influence of the experimental factor on tuber yields varied between the study years. Generally, higher yields were recorded in the case of 'Hermes' variety (crisps), harvested at the turn of August and September, compared with 'Zorba' variety (French fries), harvested in the third week of July. Statistically significant differences in 'Hermes' variety were found only in the year 2014 (Table 4), both as compared to the control variant and between the objects under analysis. The observed increase in yield was 23% under the two-fold application of potassium sulfate, while in the case of objects (ii Micro) and (iii SOP+Micro) it was 18% and 15%, respectively. For the remaining study years, an increasing trend in tuber yields was observed as a reaction to both foliar fertilizations with SOP (on average by 3.3%) and application of micronutrients (on average by 5%). A weak response of potato to potassium foliar fertilization was probably due

to the sufficient presence of available K in the soil, and to the high rate of soil fertilization with potassium. In an own study, the soil content of available K fluctuated in the range of 125–166 ppm, whereas the amount of K introduced to the soil with mineral fertilizers fluctuated from 163 to 193 ppm. According to the literature data potato response varied depending on the abundance of available K in the soil and the rate of K input with mineral fertilizers, and in many cases, the results were quite divergent. Positive effect of increasing K rates on potato yield was established by Al-Moshileh et al. (2005), while Davenport and Bentley (2001) demonstrated no response in potato yields under the influence of fertilization with potassium if K supply of the soil was low and ranged 87–154 ppm. Studies made by Curwen (1992), Tindall and Wastermann (1994, 1995), under conditions of soils rich in available potassium did not show either any response to potassium fertilization. Whereas, White (2013) and Zorb et al. (2014) indicated that in the majority of soils, even with the high soil K contents, the amount of available potassium was often insufficient to achieve the maximum yield and therefore, additional K sources are necessary to provide for an optimal plant growth performance and yield.

'Zorba' variety (French fries) was found to respond differently to foliar application of potassium sulfate and micronutrients. In that case, the experimental factor differentiated the yield of tubers in each study year, but the statistically significant increase, as compared to the control, was found only in 2016, in Micro treatment (15%) (Table 5). Whereas, in the years 2014–2015 a trend of decreasing yields was recorded, which was most pronounced for variants: (i) SOP in 2014 (decrease by 18.3%) and (ii) Micro in 2015 (decrease by 17.3%). Varying between the respective years, potato yield responsiveness to foliar fertilization and, in particular, that of the variety having a shorter vegetation period, may result from a higher sensitivity of this particular variety to changeable weather conditions during its growth. Changing weather conditions at the site, like precipitation and temperature, may influence the yield through the modification of the growth rate and crop developmental stages. However, foliar application, like soil application, is also less effective when soil moisture is limited.

Of the three study years, the growing season 2016 displayed the most favorable weather conditions for potato growth, development and yield due to a comparatively higher precipitation amount and higher temperatures in July and August (Table 3). The optimum amount of rainfall during the growing season is estimated at about 350 mm (Głuska, 1994). Potato shows the greatest demand for water at the stages of flowering and tuber formation. Under conditions of the present study, suitable rainfall amounts during this period resulted in higher potato yields as compared to those obtained in 2014 and 2015. Potato water requirements change over the growing period, and depend on the variety and its earliness, plant external characteristics, as well as the date and density of planting along with other agro-technical factors. In addition, potato plants strongly respond to hydration conditions, especially in the period from flowering to tuber formation. In the case of medium-early varieties, the critical period in plant water management lasts from the second decade of June to the end of July, and for late varieties the most important are July and August (Nowak, 2006).

Quality of tubers

1. Evaluation of protein, starch and dry matter contents.

The content of dry matter and its changes in tuber chemical composition are very important, especially in view of potato nutritional value and usefulness for culinary purposes.

The contents of dry matter and starch in tubers depend mainly on the genetic features of potato varieties (Jansen et al., 2001; Mazurczyk, 1988; Roztropowicz, 1989) as well as on environmental factors. As regards potato dietary value, changes in the protein content are essential, as proteins have a high nutritional value attributable to their amino acid composition. A special position among the components of potato tubers is taken by true proteins, which comprise 35–65% of tuber nitrogen compounds. Tuber proteins contain all the essential amino acids and are considered as valuable as animal proteins (Leszczyński, 1994). The influence of the experimental factor on the protein content varied depending on the analyzed potato variety and the year of the study (Tables 4 and 5). Statistically significant differences in the content of the analyzed parameter as compared to the control as well as between the treatments were found only in 'Zorba' variety in 2014 (Table 5). Then, foliar fertilization with potassium sulfate and micronutrients, resulted in a decreasing trend observed in tuber protein content, which was declining in

the following order: NPK+SOP> NPK+SOP+ Micro> NPK+ Micro. Over the following two years of study, the highest protein contents were noted in the treatment with double application of micronutrients, and were respectively 99.50 g kg⁻¹ (2015) and 89.58 g kg⁻¹ (2016). Studies by Kozera et al. (2003) demonstrated that fertilization with micronutrients was one of the factors that could account for biological value of potato tubers. Achieving positive qualitative results in potato cultivation is possible thanks to the use of micronutrient fertilizers with a significant addition of elements such as boron, copper and manganese.

Consistent with Kozera et al. (2003), boron in a special way promotes the transformation of larger amounts of amino acids into proteins, which increases their biological value. Likewise, the role of copper and molybdenum is manifested in improving the quality of potato tuber protein. In the case of 'Hermes' variety, the protein content was on average by 10% higher as compared to 'Zorba', and ranged from 7.8% to 11.6% (Table 5). Foliar fertilization with K and micronutrients tended to only slightly increase the protein content in the study year 2014, whereas in the remaining study years a reverse relationship was observed. No statistically significant differences were found between the treatments.

Next to the protein content, potato nutritional value comprises other parameters, i.e., dry matter and starch contents. The experimental factor significantly differentiated the content of starch in tubers of both potato varieties examined (Tables 4 and 5). In 2014 and 2015, as compared to the control, a decreasing trend was noted in the tuber starch content due to foliar fertilization with SOP and SOP + Micro. On the other hand, the reverse effect of the experimental factor on tuber starch content was observed in 2016. A statistically significant increase in the starch content compared to the control was demonstrated only for 'Hermes' variety (on average 14%). The dry matter and starch contents in potato tubers depend on a variety of environmental factors, including soil fertility, air temperature, as well as the amount and distribution of precipitation (Yusuph et al., 2003; Darwish et al., 2006). Kumar et al. (2007) reported that the percentage of dry matter in tubers was higher after soil application of K as potassium sulfate and nitrate when compared to potassium chloride. For the needs of potato processing, tubers have to contain large dry matter amounts to avoid extensive fat absorption during processing into products such as French fries and crisps (Fontes et al., 2010).

2. Tuber yield structure. In the case of potatoes cultivated for early harvesting, it is essential to obtain commercial yield in a short time, hence, tuber fraction with the diameter above 28 mm is of great importance, and this is addressed normatively in the Regulation of the Minister of Agriculture and Rural Development of 29 October 2003. Four fractions of tubers (Tables 4 and 5), were evaluated in the present study. The applied variants of foliar fertilization significantly affected the yield structure of both potato varieties analyzed.

In the case of the variety cultivated for French fries, the experimental factor significantly differentiated the tuber yield structure in the study years. Statistically significant differences were found for all the analyzed tuber fractions, although the way foliar treatments affected individual fractions was ambiguous in the successive study years (Table 5). As compared to the control, foliar fertilization with SOP and micronutrients significantly increased the share of >60 mm tuber fraction only in 2016. In the study years, the share of large tubers in the total yield ranged from 32% to 74%. Trehan et al. (2001) suggested that K increases the size of potato tubers but not the number.

Depending on the treatment, the proportion of tubers with the crosswise diameter over 60 mm in the total yield of 'Hermes' variety varied in a wide range from 56% to 86% (Table 4). The largest increase in >60 mm tuber fraction as compared to the control was observed for the variants fertilized with micronutrients (1% in 2014 and 17% in 2015). When compared to the control, statistically significant differences between the effects of the experimental factor were determined only in 2015. The effect of foliar fertilization varied in the remaining study years and when compared to the control, an upward trend was observed only in 2016.

Conclusions

Joint foliar application of potassium in the form of potassium sulfate together with micronutrients yields various results in potato cultivation technology, depending upon the analyzed variety. Irrespective of the study year, the positive effect of the experimental factor, expressed in terms of the increased yield, was more pronounced in the case of potato variety having a longer vegetation period. Two-fold application of potassium sulfate at the total rate of 8.6 kg ha⁻¹ increased yield within the range from 2 to 23% during the study years. Foliar fertilization with micronutrients increased the level of yield within the limit from 2.6 to 7%. However, to arrive at a conclusion more research work should be carried out at different areas.

Acknowledgments

The authors would like to cordially thank Tessengerlo Group for financial support of this project. We express our sincere thanks to Dr. Anna Budka for statistical consultation as well as for valuable suggestions and comments on the manuscript.

References

- AbdelGadir, A.H., Errebhi, M.A., Al-Sarhan, H.M., and Ibrahim, M. (2003). The effect of different levels of additional potassium on yield and industrial qualities of potato (*Solanum tuberosum* L.) in irrigated arid region. *Am. J. Potato Res.* 80, 219–222. <https://doi.org/10.1007/BF02855694>.
- Al-Moshileh, A., Errebi, M., and Motawei, M. (2005). Effect of various potassium and nitrogen and splitting methods on potato under sandy soil and arid environmental conditions. *Emirates J. Agric. Sci.* 17, 1–9. <https://doi.org/10.9755/ejfa.v12i1.5043>.
- Amtmann, A., Hammond, J.P., Armengaud, P., and White, P.J. (2006). Nutrient sensing and signalling in plants: potassium and phosphorus. *Adv. Bot. Res.* 43, 209–257. [https://doi.org/10.1016/S0065-2296\(05\)43005-0](https://doi.org/10.1016/S0065-2296(05)43005-0).
- Barracough, P.B., and Haynes, J. (1996). The effect of foliar supplements of potassium nitrate and urea on the yield of winter wheat. *Fert. Res.* 44, 217–223. <https://doi.org/10.1007/BF00750928>.
- Bienia, B., Sawicka, B., and Krochmal-Marczak, B. (2018). Impact of foliar fertilization based on macroelement fertilizers on yielding and structure of yield in several potato cultivars. *Fragm. Agron.* 35(1), 17–28.
- Blachinski, D., Shtienberg, D., Dinoor, A., Kafkafi, U., Sujkowski, L.S., Zitter, T.A., and Fry, W.E. (1996). Influence of foliar application of nitrogen and potassium on *Alternaria* diseases in potato, tomato and cotton. *Phytoparasitica* 24(4), 281–292. <https://doi.org/10.1007/BF02981411>.
- Blagoeva, V., Iliev, E., and Nikolova, E. (2004). Potatoes cultivation, diseases and pests, and storage (Sofia, Bulgaria: Enjovche), 105 pp.
- Boligłowa, E. (2003). The effects of varied soil and foliar mineral fertilization levels in the production of high-starch potatoes. *Acta Agroph.* 85, 99–106.
- Carew, R., Khakbazan, M., and Mohr, R. (2009). Cultivar developments, fertilizer inputs, environmental conditions, and yield determination for potatoes in Manitoba. *Am. J. Potato Res.* 86, 442–455. <https://doi.org/10.1007/s12230-009-9099-6>.
- Curwen, D. (1992). Influence of potassium and nitrogen management on potato tuber dry matter and bruising. *Proceedings Wisconsin Fertilizer, Agrilime and Pest Management Conference* 31, 97–101. (Madison WI, USA: Dept. of Soil Science, University of Wisconsin-Madison).
- Czyżyk, F. (2011). Consumption of mineral fertilizers on the farms evaluated in aspect of environmental protection. *Prob. Agric. Engin.* 19(3), 69–76.
- Daccache, A., Weatherhead, K., Stalham, M.A., and Knox, J.W. (2011). Impacts of climate change on irrigated potato production in a humid climate. *Agric. For. Meteorol.* 151(12), 1641–1653. <https://doi.org/10.1016/j.agrformet.2011.06.018>.
- Darwish, T.M., Atallah, T.W., Hajhasan, S., and Haidar, A. (2006). Nitrogen and water use efficiency of fertigated processing potato. *Agric. Water Manag.* 85, 95–104. <https://doi.org/10.1016/j.agwat.2006.03.012>.
- Davenport, J.R., and Bentley, E.M. (2001). Does potassium fertilizer influence potato yield and quality in the Columbia Basin? *Am. J. Potato Res.* 78, 311–318. <https://doi.org/10.1007/BF02875696>.
- De Jong, H. (2016). Impact of the potato on society. *Am. J. Potato Res.* 93(5), 415–429. <https://doi.org/10.1007/s12230-016-9529-1>.
- Egnér, H., Riehm, H., and Domingo, W.R. (1960). Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoff-zustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. *Kungl. Lanthr. Hogsk. Ann.* 26, 199–215.
- Erismann, W., Sutton, M.A., Galloway, J.N., Klimont, Z., and Winiwarter, W. (2008). How a century of ammonia synthesis changed the world? *Nat. Geo. Sci.* 1, 636–639. <https://doi.org/10.1038/ngeo325>.
- Fageria, N.K., Barbosa Filho, M.P., Moreira, A., and Guimarães, C.M. (2009). Foliar fertilization of crop plants. *J. Plant Nutr.* 32(6), 1044–1064. <https://doi.org/10.1080/01904160902872826>.
- Fontes Paulo, C.R., Braun, H., Busato, C., and Cecon, P.R. (2010). Economic optimum nitrogen fertilization rates and nitrogen fertilization rate effects on tuber characteristics of potato cultivars. *Potato Res.* 53, 167–179. <https://doi.org/10.1007/s11540-010-9160-3>.
- Gaj, R., Murawska, B., Fabisiak-Spychaj, E., Budka, A., and Kozera, W. (2018). The impact of intercrops and foliar application of micronutrients on the accumulation of macronutrients in potato tubers during the physiological maturity phase. *Eur. J. Hortic. Sci.* 83(6), 345–355. <https://doi.org/10.17660/eJHS.2018/83.6.2>.
- Girma, K., Martin, K.L., Freeman, K.W., Mosali, J., Teal, R.K., Raun, S.W., Moges, S.M., and Arnall, D.B. (2007). Determination of optimum rate and growth for foliar applied phosphorus in corn. *Commun. Soil Sci. Plant.* 38, 1137–1154. <https://doi.org/10.1080/00103620701328016>.
- Gluska, A. (1994). The influence of rainfall amounts and rainfall distribution in the main months of potato vegetation period (VI–IX) on the yield in relations to planting dates and cultivar earliness. *Biul. Inst. Ziemniaka* 44, 65–82 (in Polish).
- Gruczek, T. (2004). Natural and agrotechnical effects of potato cultivation. *Zesz. Probl. Post. Nauk Rol.* 500(4), 31–44 (in Polish).
- GUS (2018). Statistical Yearbook of Agriculture. Crop Production in 2017.

- Jansen, G., Flamme, W., Shüler, K., and Vandrey, M. (2001). Tuber and starch quality of wild and cultivated potato species and cultivars. *Potato Res.* 44, 137–146. <https://doi.org/10.1007/BF02410100>.
- Kocoń, A. (2016). Current trends and innovations in foliar nutrition. *Studia i Raporty IUNG-PIB.* 48(2), 49–63 (in Polish).
- Kozera, W., and Barczak, B. (2007). Effect of fertilization with microelements on the protein structure. *Biul. IHAR.* 243, 167–177 (in Polish).
- Kozera, W., Nowak, K., and Cwojdzński, W. (2003). Effect of fertilization with some microelements on the content and quality of potato tuber protein. *Agricultura* 2(2), 73–82.
- Koźmiński, Cz., and Michalska, B. (2001). Atlas klimatycznego ryzyka uprawy roślin w Polsce. Szczecin. AR. ISBN-83-87327-24-7, 81 pp.
- Kumar, P., Pandey, S.K., Singh, B.P., Singh, S.V., and Kumar, D. (2007). Influence of source and time of potassium application on potato growth, yield, economics and crisp quality. *Potato Res.* 50, 1–13. <https://doi.org/10.1007/s11540-007-9023-8>.
- Lal, B., and Singh, K.B. (1983). Effect of potassium on the quality of potato (*Solanum tuberosum* L.). *Agric. Sci. Digest.* 3, 30–33.
- Lambert, D.H., Powelson, M.L., and Stevenson, W.R. (2005). Nutritional interactions influencing diseases of potato. *Am. J. Potato Res.* 82, 309–319. <https://doi.org/10.1007/BF02871961>.
- Leszczyński, W. (1994). Potato as a food product. *Post. Nauk Rol.* 1, 15–29.
- Lutomirska, B. (2008). Cultivation technology of potato for food processing. *Zesz. Probl. Post. Nauk Rol.* 530, 53–67 (in Polish).
- Marschner, P. (2012). Mineral Nutrition of Higher Plants, 3rd edn. (London: Academic Press), p. 178–189.
- Mazurczyk, W. (1988). Chemical composition of mature tubers of potato cultivars. *Biul. Inst. Ziemniaka* 37, 11–20.
- Nowak, L. (2006). Irrigation of root crops. In *Irrigation of Plants*, S. Karczmarczyk, and L. Nowak, eds. (Poznań: PWRiL), p. 367–381.
- Panique, E., Kelling, K.A., Schulte, E.E., Hero, D.E., Stevenson, W.R., and James, R.V. (1997). Potassium rate and source effects on potato yield, quality and disease interaction. *Am. Potato J.* 74, 379–398. <https://doi.org/10.1007/BF02852777>.
- Pobereźny, J., and Wszelaczyńska, E. (2011). Effect of bioelements (N, K, Mg) and long-term storage of potato tubers on quantitative and qualitative losses. Part II. Content of dry matter and starch. *J. Elem.* 16(2), 237–246. <https://doi.org/10.5601/jelem.2011.16.2.07>.
- Rębarz, K., Borówcza, F., Gaj, R., and Friske, T. (2015). Effects of cover type and harvest date on tuber yield and quality as well as on economic results of early potato cultivation. *Am. J. Potato Res.* 92, 359–366. <https://doi.org/10.1007/s12230-015-9441-0>.
- Regmi, A.P., Ladha, J.K., Pasquin, E., Pathak, H., Hobbs, P.R., Shrestha, L.L., Gharti, D.B., and Duveiller, E. (2002). The role of potassium in sustaining yields in a long-term rice-wheat experiment in the Indo-Gangetic Plains. *Biol. Fert. Soils* 36, 240–247. <https://doi.org/10.1007/s00374-002-0525-x>.
- Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 29 października 2003r. w sprawie szczegółowych wymagań w zakresie jakości handlowej ziemniaków. 2003 Dz. U. RP 194, poz. 1900.
- Roztropowicz, S. (1989). Variation in chemical composition of potatoes tubers, resulting from environmental, varietal and fertilization sources. *Frag. Agron.* 1(21), 33–75 (in Polish).
- Schachtschabel, P. (1955). Methode Schachtschabel. In *Methodenbuch, Band I. Die Untersuchung von Böden*, 3. Auflage, R. Thun, R. Herrmann, and E. Knickmann, eds. (Radebeul und Berlin: Neumann Verlag).
- Szewczuk, C., and Michałojć, Z. (2003). Practical aspects of foliar fertilization. *Acta Agroph.* 85, 19–29.
- Tilman, D., Balzer, C., Hill, J., and Befort, B.L. (2011). Global food demanded the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* 108, 20260–20264. <https://doi.org/10.1073/pnas.1116437108>.
- Tindall, T., and Westermann, D.T. (1994). Potassium fertility management of potatoes (Pocatello, ID, USA: University of Idaho Potato School (Mimeo)).
- Trawczyński, C. (2013). The effect of foliar fertilization with Herbagegreen on yielding of potatoes. *Ziemniak Polski* 2, 29–32 (in Polish).
- Trehan, S.P., Roy, S.K., and Sharma, R.C. (2001). Potato variety differences in nutrient deficiency symptoms and responses to NPK. *Better Crops Int.* 15, 18–21.
- Wang, M., Zheng, Q., Shen, Q., and Guo, S. (2013). The critical role of potassium in plant stress response. *Int. J. Mol. Sci.* 14(4), 7370–7390. <https://doi.org/10.3390/ijms14047370>.
- Westermann, D.T., and Tindall, T.A. (1995). Managing potassium in potato production systems of Idaho. *Proc. Idaho Potato School*, p. 201–220.
- White, P.J., and Karley, A.J. (2010). Potassium. In *Plant Cell Monographs 17, Cell Biology of Metals and Nutrients*, R. Hell, and R.-R. Mendel, eds. (Berlin: Springer), p. 199–224. https://doi.org/10.1007/978-3-642-10613-2_9.
- White, P.J. (2013). Improving potassium acquisition and utilization by crop plants. *J. Plant Nutr. Soil Sci.* 176, 305–316. <https://doi.org/10.1002/jpln.201200121>.
- Woolfe, J.A. (1987). The Potato in the Human Diet (Cambridge: Cambridge University Press). <https://doi.org/10.1017/CBO9780511753435>.
- Yusuph, M., Tester, F., Colin, A., and Snape, E. (2003). Composition and properties of starches extracted from tubers of different potato varieties grown under the same environmental conditions. *Food Chem.* 82, 283–289. [https://doi.org/10.1016/S0308-8146\(02\)00549-6](https://doi.org/10.1016/S0308-8146(02)00549-6).
- Zorb, C., Senbayram, M., and Peiter, E. (2014). Potassium in agriculture – Status and perspectives. *J. Plant Physiol.* 171(9), 656–669. <https://doi.org/10.1016/j.jplph.2013.08.008>.

Received: May 6, 2019

Accepted: Oct. 8, 2019

Address of authors:

Renata Gaj* and Jarosław Borowski-Beszta
 Poznan University of Life Sciences, Department of
 Agricultural Chemistry and Environmental Biogeochemistry,
 Wojska Polskiego 71F, 60-625 Poznań, Poland
 *Corresponding author; E-mail: renata.gaj@up.poznan.pl