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ORIGINAL PAPER

EFFECT OF POTASSIUM AND MICRONUTRIENT FOLIAR FERTILISATION ON THE CONTENT AND ACCUMULATION OF MACROELEMENTS, YIELD AND QUALITY PARAMETERS OF POTATO TUBERS*

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Abstract

The experiment was conducted in 2014-2016, on a farm located in western Poland. The aim was to evaluate the effect of foliar application of potassium sulphate (SOP) and micronutrients (Zn, Cu, Mn and B) on the content and accumulation of macroelements (N, K, Mg and S) in tubers at the stage of technological maturity. Two potato varieties tested in the experiment, Zorba and Hermes, are used to produce French fries and crisps, respectively. Analyses involved data from four trials, including the control where solely NPK fertilisation was applied. The other trials included: (I) double foliar treatment with SOP in the combined dose of 8.6 kg K ha^{-1}; (II) double foliar treatment with micronutrients: 12 g Zn ha^{-1}, 12 g Cu ha^{-1}, 300 g Mn ha^{-1}, and 500 g B ha^{-1}, and (III) combined application of SOP and micronutrients on two scheduled terms. The experiment was arranged in a randomised block design with four replicates for each potato variety. The experimental factor differentiated the content and uptake of macroelements, being largely controlled by changing weather conditions. Averaged across the three study years, values of nutrient accumulation in tubers showed that foliar fertilisation with potassium and micronutrients enhanced tuber K accumulation. The increase in tuber nutrient accumulation owing to foliar fertilisation was higher in the crisps variety compared to the French fries one. The regression analysis showed that the tuber yield was in 65-87% controlled by the accumulation of macroelements (N, K, Mg and S). Moreover, the protein content in both varieties was largely determined by the accumulation of macroelements in tubers, while significant relationships for the starch content were noted only in the case of the Zorba variety.

Keywords: potato varieties, nutrient uptake, specific uptake.

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INTRODUCTION

Versatile uses of potatoes in Poland and elsewhere are conditioned by many factors, out of which the most important include genetic predispositions, agricultural technology, mineral fertilisation applied and changes in technology of nutrient application (Arvanitoyannis et al. 2008, Elmore et al. 2015). Despite the short crop cycle, potatoes generally require large quantities of both macro- and micronutrients and the potato crop is very responsive to fertilisation (Kumar et al. 2007, Zhang et al. 2018). The quantitative uptake of macronutrients varies depending on an element and between genotypes (Gomez et al. 2019). One of the factors which aggravate the nutrient deficit in tubers is drought recurring from year to year, which results in an ever-increasing variation in the yields produced (Westermann 2005). Water stress decreases the nutrient absorption rate (He, Dijkstra 2014). Analyses made throughout the past decades of the relationship between yield and nutrient accessibility indicate that plant growth is predominantly limited by the nutrient availability even in arid regions (Seligman, van Keulen 1992, Swain et al. 2014). Potato is a high nutrient mining crop and needs sufficient doses of mineral fertilisation for proper growth and development (Bista, Bhabdari 2019). High yield potential, short crop cycle, shallow root system and high nutrient requirements of potato demand nutrients in a readily available form in the soil solution (Fernandes et al. 2011, Gao et al. 2018). Potato yield is greatly affected by nutrient availability, which is why research into appropriate fertiliser regimes has received much attention worldwide (Vos 2009). The amounts of mineral elements accumulated in a plant provide essential information on how to prepare a correct crop fertilisation technology. The prerequisite for obtaining high-quality tubers is to ensure a balanced crop supply with macro- and micronutrients throughout the entire growing season (Westermann 2005, Pawelzik, Möller 2014). Plant nutrient requirements have been considered mainly in quantitative categories of the need for a given mineral element, which changes with the plant development stages. Potato tuberization is the critical period for the plant's need for nutrients. At a time when the nutrient uptake from the soil is inefficient or non-existent, foliar nutrition is the best and most effective way to provide important elements to plants (Jasim, Merhij 2018). At an early growth stage, when plant roots are not well developed, foliar fertilisation is more advantageous in terms of nutrient absorption compared to soil application (Fageria et al. 2009). Therefore, there is a need to modify the current fertilization technologies by introducing foliar application of potassium and sulphur at a time when the demand for these nutrients is the highest, and by adding micronutrients in chelated forms to increase the effectivity of nitrogen use (Ierna et al. 2011). Foliar fertilisation is one of the most important methods for further processing of plant nutrients and maintaining the nutritional balance within the plant (Dkhil et al. 2011). Application of micronutrients by foliar spray is more effective because of the small amounts required (Fageria et al. 2009). Literature data concerning plant response to foliar nutrient supply generally focuses on nitrogen. The reasons may be that K is required in very high amounts by most crop plants, and K responses to field crops are limited (Fageria et al. 2009). Most of the studies related to potassium nutrition concentrate on the evaluation of yield producing potential of the nutrient applied to the soil in various forms and doses (Fageria et al. 2001, Kumar et al. 2007). In contrast, the effect of foliar potassium application on the accumulation of elements in tubers at the stage of technological maturity has been less frequently discussed. Crop responses to foliar fertilisation have been mixed, both positive, negative or no responses, depending on crop species and nutrient applied (Jasim et al. 2018). The divergence of the results indicates the need for further studies, which may include foliar fertilisation as a tool to contribute to a more sustainable and environmentally friendly potato production. Foliar application of mineral elements involves also an economic aspect (Kumar et al. 2007). If foliar fertilisation is mixed with postemergence herbicides, insecticides, or fungicides, the probability of yield response could be increased, and the cost of an application can be reduced (Fageria et al. 2008).

In the present study, it was assumed that foliar application of potassium and micronutrients at the early tuberization stage did not affect the content of macroelements in tubers. This hypothesis was verified in a single factor experiment. The objective of the study was to evaluate the effect of foliar application of potassium sulphate and micronutrients on the contents and accumulation of nitrogen, potassium, sulphur and magnesium in tubers at the stage of technological maturity.

MATERIALS AND METHODS

Field trials were made at Pierzchno (52°15′N,17°06′E) in 2014-2016. The experiment was established on light soils, the IVb quality class. 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), high for magnesium (61-80.6 mg Mg kg^{-1} soil, assessed with the Schachtschabel (1954) method. The amount of mineral N (Nmin) was 75-148 kg ha^{-1} (0.01 M $CaCl_2$). Soil pH was 6.3-7.2 (1 M KCl). Cattle manure at a dose of 20 t ha^{-1} was applied in the fall to all experimental plots. Winter wheat was grown as the preceding crop for both potato varieties examined in each year of the study.

Due to the selection of experimental potato varieties with a different length of the growing period and different way of tuber use, the varieties were not treated as an experimental factor. The one-factor experiment was established using a randomised block design with four replicates for each fertilisation treatment. Four trials were analysed, including the control, where only NPK fertilisation was applied. Consistent with the experimental design, other trials included: (I) double foliar treatment with potassium sulphate in the combined dose of 8.6 kg K ha^{-1} (acronym SOP); (II) double foliar treatment with micronutrients: 12 g Zn ha^{-1}, 12 g Cu ha^{-1}, 300 g Mn ha^{-1} and 500 g B ha^{-1} (acronym Micro) and (III) combined application of SOP and Micro on two scheduled terms (acronym SOP+Micro). Foliar treatments with potassium (SOP) and micronutrients (Micro) were carried out on potato plants growing on the soil also fertilised with nitrogen, phosphorus, potassium (NPK). Nitrogen was applied into the soil in the spring, immediately before potato tuber planting, in a split-dose system, using different N forms, i.e. (1) ammonium phosphate and (2) Urea-Ammonium Nitrate solution plus Sulphur (UAN+ S), 26% N+3% S. In the fall, fertilisation with one dose of phosphorus and potassium was carried out in the site designated for cultivation of the Zorba variety, French fries (Aviko, Netherlands), whereas in the case of the Hermes variety, crisps (Nieder Österreichische Saatbaugenossenschaft, Austria), potassium was applied in a spilt dose (one in the fall and one in the spring). Phosphorus was introduced into the soil as diammonium phosphate, DAP, Grupa Azoty Police (18% N, 20.05% P) at a dose of 30-40 kg P ha^{-1}. Potassium was applied as potassium salt (Korn Kali, K+S Polska), 33.2% K, 3.62% Mg, 5.01% S, 1.48% Na, at a dose 120-190 kg K ha^{-1}. Detailed description of the methodology is provided by Gaj, Borowski (2020).

Foliar fertilisation with potassium and micronutrients was performed twice during the growing season. The first foliar application of potassium as K_2SO_4 (43.1% K and 18.42% S Tessenderlo Group, Belgium) and micronutrients was carried out at the beginning of tuberization (BBCH 40), and the second one - two weeks later. Micronutrients were applied as chelates (boron as disodium tetraborate). All the experimental foliar treatments consisted of the total of 8.6 kg K ha^{-1} and the following quantities of micronutrients: zinc – 12 g ha^{-1}, copper – 12 g ha^{-1}, manganese – 300 g ha^{-1} and boron – 500 g ha^{-1}.

Chemical analysis

For the chemical analysis, fresh potato tubers were rinsed with deionized water, cut into small pieces and dried at 65°C for 72 h to obtain dry weight (DW), then ground in a mill. The plant tissue levels of nitrogen, sulphur and carbon were analysed on the Vario Max Analyzer, Elementar Company.

For determinations of the other nutrients, plant samples were mineralised at 600°C. The ash was mixed with 2 cm^3 of dissolved HNO_3 (concentrated nitric acid and distilled water 1:1). The concentration of Mg was determined using an atomic absorption spectrometer Varian Spectra 220 FS. The potassium content was assessed by the FAAS method (Flame Atomic Absorption Spectrophotometry), on a Varian Spectra 220 FS (Jones, Case 1990). The starch content was determined using the Reiman-Parow scale. The protein content was calculated based on the values of the nitrogen content multiplied by the coefficient 6.25. Nutrient uptake was calculated as: Element uptake expressed as kg ha^{-1} = (element content [g kg^{-1}] x dry mass yield [kg ha^{-1}])/1000; Dry mass yield = DM content [g kg] x fresh mass yield (tubers yield) [kg ha^{-1}]. Data on potato yields obtained are provided by Gaj, Borowski (2020).

Statistical tests

The results of the plant nutrient content were tested with ANOVA using Statistica® 10 (StatSoft, Krakow, Poland). The differences between the treatments were evaluated using the Tukey's test. The correlation between the potential yield (tuber fresh weight, Mg ha^{-1}) and the tuber nutrient content was determined with the Pearson correlation analysis ($p<0.05$). Multiple regression analysis was applied for the evaluation of cause-effect relationships between the parameters examined. Principal component analysis (PCA) was performed to investigate the effect of foliar application of potassium sulphate and micronutrients on the content and accumulation of macroelements, and to identify which parameters decide about the differentiation of tuber yield and quality at the most. PCA was done using the R package FactoMine R.

RESULTS AND DISCUSSION

Macroelements content

Analysis of variance showed that the content of basic macroelements in tubers at the technological maturity stage varied, depending on experimental treatment, element and year of study. For the Zorba variety, the experimental factor was found to significantly differentiate the nitrogen content only in the first year of study. On the other hand, no statistically significant differences were recorded in the nitrogen content for the Hermes variety (Table 1). For the Zorba variety, the control treatment recorded the highest N content in tubers (15.1 g kg^{-1}), and this value differed significantly only from that obtained under the trial with a double dose of foliar micronutrient application (Micro). For the remaining treatments (SOP, SOP+Micro), the nitrogen content was found to be declining as compared to the control. The effect of the experimental factor on the nitrogen content over the subsequent years of study was ambiguous, as the declining trend for the N content in tubers was recorded under SOP+Micro treatment in the Zorba variety and under all treatments – in the Hermes variety (Table 1). A comparable level

Table 1

Effect of the experimental factor on the content of macroelements in potato tubers at the stage of technological maturity

Years	Treatments	Potato varieties							
		Zorba (g kg^{-1} DW)				Hermes (g kg^{-1} DW)			
		N	K	Mg	S	N	K	Mg	S
2014	control	15.11*a*	15.76*a*	0.85*a*	2.59*a*	17.21*a*	17.75*a*	0.98*a*	2.76*a*
	SOP	14.76*ab*	16.26*a*	0.84*a*	2.35*a*	18.69*a*	20.16*a*	1.05*a*	2.88*a*
	SOP+Micro	12.70*ab*	17.65*a*	0.89*a*	2.12*a*	15.83*a*	20.26*a*	1.01*a*	2.06*a*
	Micro	11.47*b*	16.68*a*	0.79*a*	2.15*a*	17.44*a*	18.46*a*	1.02*a*	2.41*a*
2015	control	15.86*a*	18.47*a*	0.80*a*	1.71*a*	18.13*a*	15.47*a*	0.80*a*	2.25*ab*
	SOP	14.49*a*	17.63*a*	0.73*a*	1.64*a*	16.74*a*	18.18*a*	0.96*a*	2.12*b*
	SOP+Micro	15.28*a*	17.52*a*	0.74*a*	1.97*a*	16.54*a*	17.67*a*	0.84*a*	2.70*a*
	Micro	15.92*a*	18.80*a*	0.92*a*	2.34*a*	16.85*a*	18.28*a*	0.91*a*	1.96*b*
2016	control	11.77*a*	16.70*b*	0.89*a*	1.99*a*	18.13*a*	16.82*a*	0.96*a*	1.90*a*
	SOP	13.77*a*	19.22*a*	0.92*a*	1.99*a*	16.74*a*	17.12*a*	0.93*a*	2.04*a*
	SOP+Micro	12.08*a*	17.76*ab*	0.76*a*	1.67*a*	16.54*a*	18.11*a*	1.02*a*	2.22*a*
	Micro	14.93*a*	19.37*a*	0.93*a*	1.86*a*	16.85*a*	16.99*a*	0.96*a*	2.02*a*
Mean 2014-2016	control	14.25*a*	16.98*a*	0.85*a*	2.13*a*	16.51*a*	16.68*b*	0.91*a*	2.306*b*
	SOP	14.34*a*	17.72*a*	0.84*a*	1.99*a*	15.97*a*	18.49*a*	0.98*a*	2.34*ab*
	SOP+Micro	13.35*a*	17.64*a*	0.80*a*	1.92*a*	15.20*a*	18.68*a*	0.96*a*	2.65*a*
	Micro	13.90*a*	18.82*a*	0.88*a*	2.12*a*	16.07*a*	17.89*ab*	0.96*a*	2.13*b*

* Values in the same column followed by the same letter indicate a lack of significant differences within the treatment. Tukey's test (p<0.05).

of the tuber nitrogen content under different doses of potassium fertilisation was reported by other authors (Neshev, Manolov 2015). Studies by Neshev and Manolov (2015) demonstrated a decline in the tuber nitrogen content under conditions of the application of increasing potassium doses.

Foliar fertilisation with potassium and micronutrients increased the K content in tubers in both varieties examined, regardless of the year of study (Table 1). A significant increase in the content of K as compared to the control was found for only one year of study (2016) in the Zorba variety under treatments with SOP and Micro. In the remaining cases, the foliar sprays increased the K content in tubers. Regardless of the year of study, the higher content of K was recorded for the Hermes variety, within the range from 15.47 g to 20.2 g kg^{-1} DW. According to Kumar and Chandra (2018), high K concentrations of above 20 g kg^{-1} DW in tuber dry matter due to an oversupply with potassium may lower the content of dry matter. These authors suggest that about 18 g K kg^{-1} in tuber dry matter may be necessary for a high starch concentration. In line with the literature data (Winkelmann 1992), the average potassium content in tubers which secures high and high-quality yields should be contained within 22-25 g kg^{-1} DW. The above variability in the K content may be partially explained by the changing weather conditions during the treatments, which were performed at the stage of tuber initiation, since the K uptake is strongly related to the soil water content (Watson et al. 2001). Vyn, Janovicek (2001) suggest that both the cultivation system and K application technology may be the factors which differentiate the potassium content in plants. Literature data (Ierna et al. 2011), confirmed by our observations, show that the content of elements in tubers during the maturation period is influenced by many factors. This is an indication that foliar spray with K could only supplement the soil application of K (Panique et al. 1997). Whereas studies performed by Bista and Bhandari (2019) showed that soil application of K accompanied by foliar spray was more efficient than soil application alone. These authors believe that split application of potassium was better compared to the basic application. According to Askegaard et al. (2004), the evaluation of the potassium content in plants is a key element of effective potassium management and is complementary to soil tests. Recent studies on the global scale demonstrate that potassium limits the production of ca. 70% of the investigated ecosystems (Sardans, Peñuelas 2015), thus the K nutrient management has become a major research topic (Zőrb et al. 2014).

A synthesis of the results obtained over the three study years showed the lack of significant differences in the tuber magnesium content. As compared to the control, there was only a trend to an increasing magnesium content in tubers (Hermes variety) under the treatment with foliar sprays. The average value of this nutrient ranged from 0.80 to 0.98 g kg^{-1}. For the French fries variety, the experimental factor did not have an unambiguous effect on the tuber magnesium content. A growing trend for the magnesium concentration was observed in tubers from the Micro treatment as compared to the control (Table 1). Whereas, the sulphur content in tubers behaved differently, as it varied between the treatments analysed in the subsequent years of study (Table 1). The average S content was contained in the range from 1.92 to 2.65 g kg^{-1}. Moreover, the S content in tubers varied greatly between the years of study and was closely related to the weather pattern during the growing season. High temperatures coupled with the lack of precipitation during the plant growing season of 2015 resulted in both lowered yields and low concentrations of sulphur in plants. Generally, the foliar spray with potassium sulphate repeated twice did not affect the content of sulphur in tubers, regardless of the year of study. According to Wang et al. (2008), potato is not considered a high S-demanding crop, with S concentrations ranging from 1.2 to 2.8 g kg^{-1} in the dry matter of tuber and haulm, but considerable amounts of S can be removed from the soil over the long term when yields are high (Carew et al. 2009, Klikocka 2015).

For the Hermes variety, the analysis of the correlation between the yield of tubers at the stage of technological maturity, the qualitative parameters (starch, proteins) and the tuber content of nitrogen, potassium, magnesium and sulphur did not indicate any statistically significant relationships. Koch et al. (2019) reported that due to their various functions in plant metabolism, the impact of plant nutrients on potato yield and quality parameters is complex. The relationship between the tuber carbon content and yield was also analysed. Regardless of the experimental treatment, there were significant relationships, expressed by the values of correlation coefficients: control 0.774, SOP 0.663, SOP+Micro 0.863 and Micro 0.816.

Another factor important for the content of a given nutrient in plants is the concentration of the remaining elements. Concentrations of nutrients change relative to one another within the soil and plant throughout the plant growth. These changes can create nutrient interactions, which are likely to result from a combination of synergistic and antagonistic soil and plant processes which affect crop response, either directly or indirectly (Fixen et al. 2005, Zhang et al. 2007, Roberts 2008). In the present study, the analysis of correlations between the tuber yield and the ratios of the following elements: N:S, N:K, N:Mg and C:N showed significant positive relationships only in the case of the C:N ratio for all treatments with the crisps variety (Hermes) – Table 2. Significant positive relationships were also determined

Table 2

Correlation analysis of the relationships between tuber yield and pairs of macroelements in potato tubers

Potato varieties	Treatments	N:K	N:S	N:Mg	C:N
Zorba	control	-0.208	-0.840***	-0.778**	0.634*
	SOP	-0.505	-0.412	-0.651*	0.084
	SOP+Micro	-0.659*	-0.240	-0.549*	0.606*
	Micro	-0.322	0.210	-0.274	0.153
Hermes	control	-0.377	-0.462	-0.328	0.603*
	SOP	-0.622*	-0.743**	-0.656*	0.809**
	SOP+Micro	-0.396	-0.592*	-0.503	0.645*
	Micro	-0.217	-0.341	-0.344	0.432

***, **, * significant at p<0.001, <0.001, <0.05, respectively

for the control and SOP+Micro for the French-fries variety (Zorba). Processes of plant growth are closely connected with the metabolism of carbon and nitrogen. Organic compounds produced in leaves are transported to storage organs, here potato tubers.

The results of the present study showed that relations expressing the ratios of element content in tubers were significantly correlated with the protein content (Table 3). The present results confirm the thesis put forward by Marschner et al. (1996) about the interaction of nitrogen, potassium, magnesium and sulphur. The N:S ratio in the plant matches the rela-

Table 3
Correlation analysis of the relationships between protein content and pairs of macroelements in potato tubers

Potato varieties	Treatments	N:K	N:S	N:Mg	C:N
Zorba	control	0.753**	0.641*	0.860**	-0.997***
	SOP	0.691*	0.246	0.320	-0.993***
	SOP+Micro	0.917***	-0.221	0.583	-0.948***
	Micro	0.823**	0.732**	0.599*	-0.985***
Hermes	control	0.648*	0.974***	0.601*	-0.972***
	SOP	0.773**	0.941***	0.793**	-0.992***
	SOP+Micro	0.785**	0.922***	0.649*	-0.981***
	Micro	0.857**	0.973***	0.645*	-0.959***

***, **, * significant at p<0.001. <0.01. <0.05, respectively

tionship between the two components, and the narrower its value is in individual organs, the more efficient is the nitrogen use in plants, which translates into a greater yield of the useful organ. For the analysed varieties, the N:S relation was in the range 4.3-4.6:1 for Hermes and 6.8-7.4:1 for Zorba. Sulphur influences the activity of the enzymes participating in the reduction of nitrates, thus a S deficit results in the accumulation of non-protein forms of nitrogen as a consequence of a disturbed N:S ratio, the average value of which for potato is 11:1 (Klikocka et al. 2003).

In contrast to the relationship between potato yield responses and the C:N ratio, no similar relationships were observed for the tuber protein content and the C:N ratio (Table 3). A strong negative correlation was demonstrated for the latter relationships in all cases.

Nutrient uptake

According to the one-way ANOVA performed, the accumulation of nitrogen, potassium and sulphur in tubers at the technological maturity stage varied due to the effect of the experimental factor and depending on the potato variety examined. Regardless of the year of study, the differentiating effect of the experimental factor on micronutrient accumulation in the dry tuber mass was higher in the French fries than in the crisps variety. Moreover, a higher level of macronutrient accumulation was noted for the Hermes than for the Zorba variety. These differences were due to a higher yield and later date of tuber harvest. Gómez et al. (2019) emphasises that assimilate transportation from the aerial organs to tubers at the stage of maturity may be extended through an extended duration of leaf area. Significant differences in nitrogen uptake as affected by foliar sprays were noted between the Zorba variety and the control in both years of study (2014 and 2016), while the effect of the experimental factor varied by year. In the first year of study, the highest value of N uptake, i.e. 151 kg N ha^{-1}, was found for the control.

Introduction of foliar sprays significantly decreased the nitrogen uptake, and there was a 59% difference between the control and the treatment, which took the least amount of N (Micro). There were also statistically significant differences in nitrogen accumulation between the treatments SOP+Micro and Micro. A reverse relationship was observed for the impact of foliar sprays on nitrogen uptake in the third year of study. The two-fold foliar spray of potassium and micronutrients significantly increased the uptake of nitrogen, which amounted to 10.4% (SOP+Micro) and 48.5% (Micro) compared with the control.

In contrast, the experimental factor did not have any significant impact on the Hermes variety in terms of the differences in nitrogen accumulation (Table 4). The values of N uptake ranged from 154 to 222.23 kg N ha^{-1}. The synthesis of results from the three study years showed that the average nitrogen uptake by the Hermes variety was 185.7 kg N ha^{-1} for the control, while the results for the other treatments were: SOP – 196.4 kg; SOP + Micro 176.3 kg N and 202.3 kg N ha^{-1} (Micro).

No increased nitrogen accumulation in variety Zorba tubers was observed due to the effect of the experimental factor and between the treatments ana-

Table 4

Effect of experimental factor on nutrients' uptake by potato tubers at the stage of technological maturity (kg ha^{-1})

Years	Treatments	Potato varieties							
		Zorba				Hermes			
		N	K	Mg	S	N	K	Mg	S
2014	control	151.29*a*[#]	157.47*ab*	8.56*a*	25.93*a*	162.01*a*	166.81*a*	9.15*a*	26.16*a*
	SOP	103.14*bc*	113.12*c*	5.86*b*	16.44*b*	208.15*a*	224.98*a*	11.75*a*	32.09*a*
	SOP+Micro	117.25*b*	164.60*a*	8.31*a*	19.40*ab*	154.70*a*	197.59*a*	9.90*a*	29.76*a*
	Micro	88.41*c*	128.16*c*	6.08*b*	16.41*b*	192.81*a*	203.27*a*	11.12*a*	26.68*aa*
2015	control	111.37*a*	129.45*a*	5.64*a*	12.05*a*	204.32*a*	173.31*a*	9.05*a*	25.31*a*
	SOP	94.45*a*	115.09*a*	4.95*a*	10.71*a*	192.44*a*	208.82*a*	11.02*a*	24.24*a*
	SOP+Micro	92.83*a*	105.41*a*	4.39*a*	12.13*a*	170.61*a*	180.98*a*	8.63*a*	28.28*a*
	Micro	96.07*a*	113.89*a*	5.69*a*	14.03*a*	191.99*a*	206.11*a*	10.35*a*	22.19*a*
2016	control	123.91*a*	175.28*b*	9.38	20.92*a*	190.87*a*	226.27*b*	12.97*a*	25.61*a*
	SOP	145.39*ab*	203.87*ab*	9.75	21.19*a*	188.52*a*	259.01*ab*	14.25*a*	30.79*a*
	SOP+Micro	136.87*b*	201.47*b*	8.77	19.00*a*	203.73*a*	278.15*a*	15.77*a*	34.05*a*
	Micro	183.96*a*	248.80*a*	11.91	23.96*a*	222.23*a*	272.46*a*	15.52*a*	32.39*a*
Mean 2014--2016	control	128.86*a*	154.06*a*	7.86*a*	19.63*a*	185.73*a*	188.80*b*	10.39*a*	25.69*a*
	SOP	114.33*a*	144.06*a*	6.85*a*	16.11*a*	196.37*a*	230.93*a*	12.34*a*	29.04*a*
	SOP+Micro	115.65*a*	157.16*a*	7.16*a*	16.85*a*	176.34*a*	218.91*a*	11.43*a*	30.69*a*
	Micro	122.82*a*	163.62*a*	7.90*a*	18.14*a*	202.34*a*	227.28*a*	12.33*a*	27.09*a*

[#] Values in the same column followed by the same letter indicate a lack of significant differences within the treatment, Tukey's test (p<0.05).

lysed. Compared to the control, the largest decline in N accumulation was noted for the SOP and SOP+Micro treatments. Singh and Lal (2012) reported that the total uptake of N and K increased with increasing levels of potassium application. The above authors found the highest nitrogen (116.2 kg ha^{-1}) and potassium (167.2 kg ha^{-1}) uptake at the K_2O dose of 150 kg ha^{-1}. In the authors' research, foliar fertilisation (potassium and micronutrients) had a more important effect on the variability of potassium accumulation in tubers of both tested varieties, while the values of accumulation fluctuated in a wide range from 105 to 278 K ha^{-1}. Among the nutrients analysed, the highest uptake was noted for potassium, which is consistent with literature data (Kumar, Chandra 2018).

Similarly to nitrogen, the highest values of K uptake for all the analysed treatments were recorded in 2016 (Table 5) and were the result of an in-

Table 5

Regression models of potato yield, protein and starch content as the function of macroelement uptake at physiological maturity of potato tubers

Potato varieties	Quality parameter	Regression models	R^2
Hermes	y (yield)	*y* = 0.0192UpN + 0.0159UpS + 0.1254UpK + 0.5804UpMg + 19.5392 (0.48) (0.91) (*) (.29) (*)	0.6695
Zorba		*y* = -0.0292Up N + 0.5112Up S + 0.1789Up K + 0.2430Up Mg + 12.191 (0.45) (*) (*) (*) (*)	0.8701
Hermes	y (protein)	*y* = 0.4334Up N + 0.0331Up S - 0.2330Up K - 1.1411Up Mg + 79.9858 (*) (.91) (*) (.29) (*)	0.6384
Zorba		*y* = 0.7139Up N - 1.2466Up S - 0.4083Up K + 0.6412Up Mg + 81.7721 (*) (*) (*) (0.59) (*)	0.6933
Hermes	y (starch)	*y* = 0.0070Up N - 0.0118Up S + 0.0051Up K + 0.1021Up Mg + 11.9340 (.23) (.70) (.95) 0.38) (*)	0.20475
Zorba		*y* = 0.0066Up N + 0.0569Up S + 0.0226Up K - 0.2546Up Mg + 9.0600 (0.43) (0.14) (*) (0.07) (*)	0.5094

Up_x – x= N, P, K macroelement uptake; * significant at $p<0.05$

crease in tuber yield as compared to previous years (results published in Gaj, Borowski (2020). Foliar fertilisation of the Zorba variety in the said year, compared to the control, increased the K accumulation in the range of 15% (SOP + Micro) to 42% (Micro), while in the case of the crisps variety (Hermes) – from 14% (SOP) to 20% (Micro). This relationship may indicate a luxurious uptake of the nutrient, as the cultivation site was characterised by an average available potassium content (125-166 ppm) and a relatively high level of soil fertilisation (163 to 193 kg K ha^{-1}). Generally, 150 kg K ha^{-1} is assumed to be the optimum dose and found to be economically profitable. However, it is recommended that K application is based on soil tests, potato variety, climatic conditions, etc. (Bista, Bhandari 2019).

The experimental factors significantly increased the potassium accumulation in dry mass of tubers of the Hermes variety, as is shown by the average values of K uptake over three years of study. As compared to the control, the highest increase was found for the SOP treatment, where it attained 22%, while for the remaining treatments, an increase was by 20% (Micro) and 16% (SOP+Micro), respectively. Kang et al. (2014) demonstrated an increase in the potassium uptake in the range from 27 to 126%, consistent with the increasing dose of K fertilisation applied. The current data suggest not only that the K uptake is strongly determined by water availability, but also that K is crucial to the strategies of water economy (Sardans, Peñuelas 2015). Naumann et al. (2019) suggested that very high accumulation of K in tubers increases the uptake of water by the tuber. This can result in dilution of the starch content, independent of the form of K application.

The lowest accumulation of sulphur and magnesium, as well as nitrogen and potassium in dry tuber mass of the Zorba variety was demonstrated for the SOP and SOP+Micro treatments (Table 4). On the other hand, Mg and S were noted to be increasingly accumulated only under the Micro treatment, and the increases were 26% (Mg) and 14% (S) compared to the control. For the other variety analysed, the experimental factor induced increased accumulation of Mg and S in tubers under all the treatments. Compared to the control, a similar level of Mg accumulation, on the average 12.31 kg Mg ha^{-1}, was recorded in the SOP and SOP+Micro treatments. Sulphur accumulation in tubers was declining in the order: SOP+Micro< <SOP< Micro<control.

The accumulation of Mg and S as a response to foliar sprays with potassium sulphate and micronutrients varied between the study years, which shows the importance of environmental factors. Some recent studies demonstrated that foliar K concentrations are negatively correlated with the mean annual precipitation (Fyllas et al. 2009, Zhang et al. 2012), whereas a few other reports provide observations of contrary relationships (Sardans et al. 2012).

Graphical interpretation of the relationships illustrating the dependence of yield on the macroelement content and accumulation in tubers for both varieties is shown using principal component analysis (PCA) – Figure 1 and Figure 2). For both varieties, significant dependences were found between tuber yields and the accumulation of all macroelements analysed in tubers. Significant relationships between tuber yield and the uptake of N, K, Mg and S were found for all treatments with the Hermes variety (Figure 1) as well as for individual elements and treatments with the variety Zorba (Figure 2). The relations between nutrient uptake and yield reflects the efficiency of nutrient utilisation expressed in economic product e.g. tubers (van Duivenbooden 1993). Although the uptake of mineral nutrients by potatoes in connection with biomass accumulation is genetically determined, but also depends on environmental factors, fertiliser doses and initial conditions of soil fertility

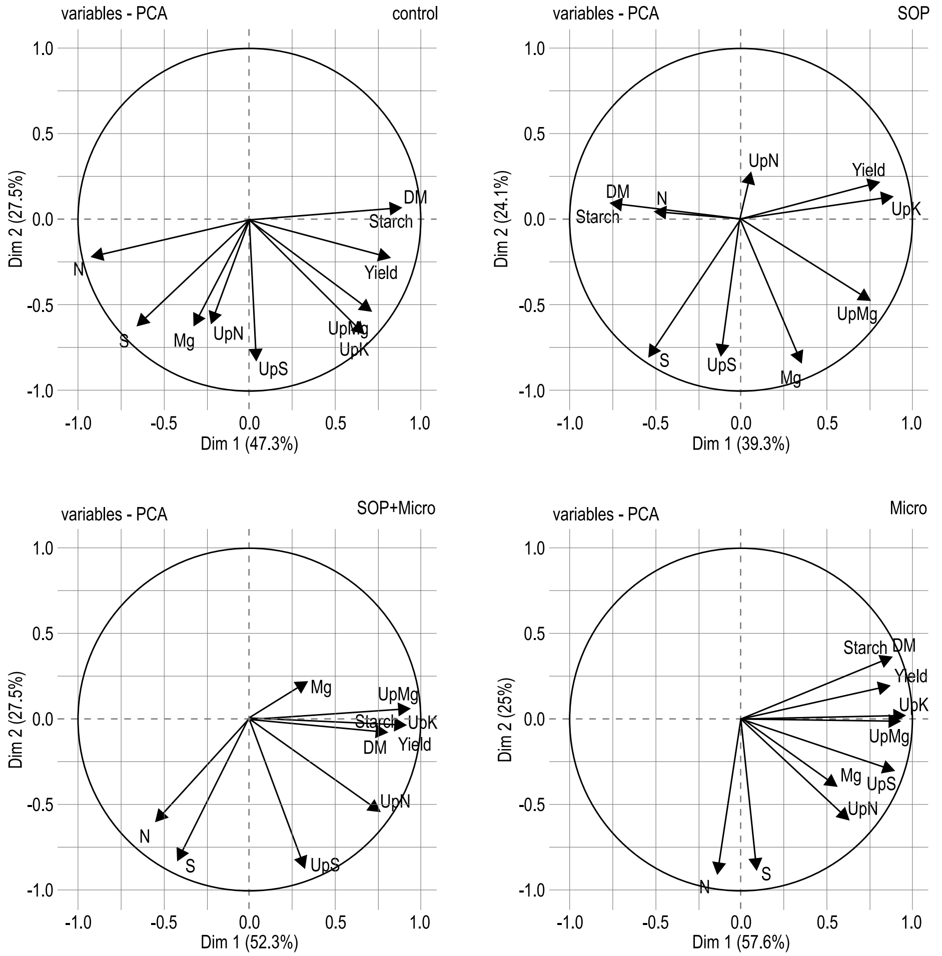

Fig. 1. Two-dimensional spatial image of variable macroelement content and accumulation as well as potato yield and quality parameters, Hermes variety: N, K, Mg S – macroelement content, UpN, UpK, UpS, UpMg – macroelement uptake, DM – dry matter

(Belanger et al. 2001, Gomez et al. 2017). Regression analysis, taking into account the dependence of yield on the accumulation of elements in tubers, showed that macroelements determined the yield in the range from 67% (Hermes) to 87% (Zorba). The regression equations in Table 5 illustrate the above relationships. The relation between nutrient uptake and yield reflects the efficiency of nutrient utilisation expressed in economic product (e.g. tubers). For both the varieties examined, significant relationships were established between the protein content and the accumulation of elements, which is confirmed by the above regression equations. The protein content was controlled by the element accumulation in 63% for the Hermes variety, and in 69% for the Zorba variety (Table 4). Both the content of element

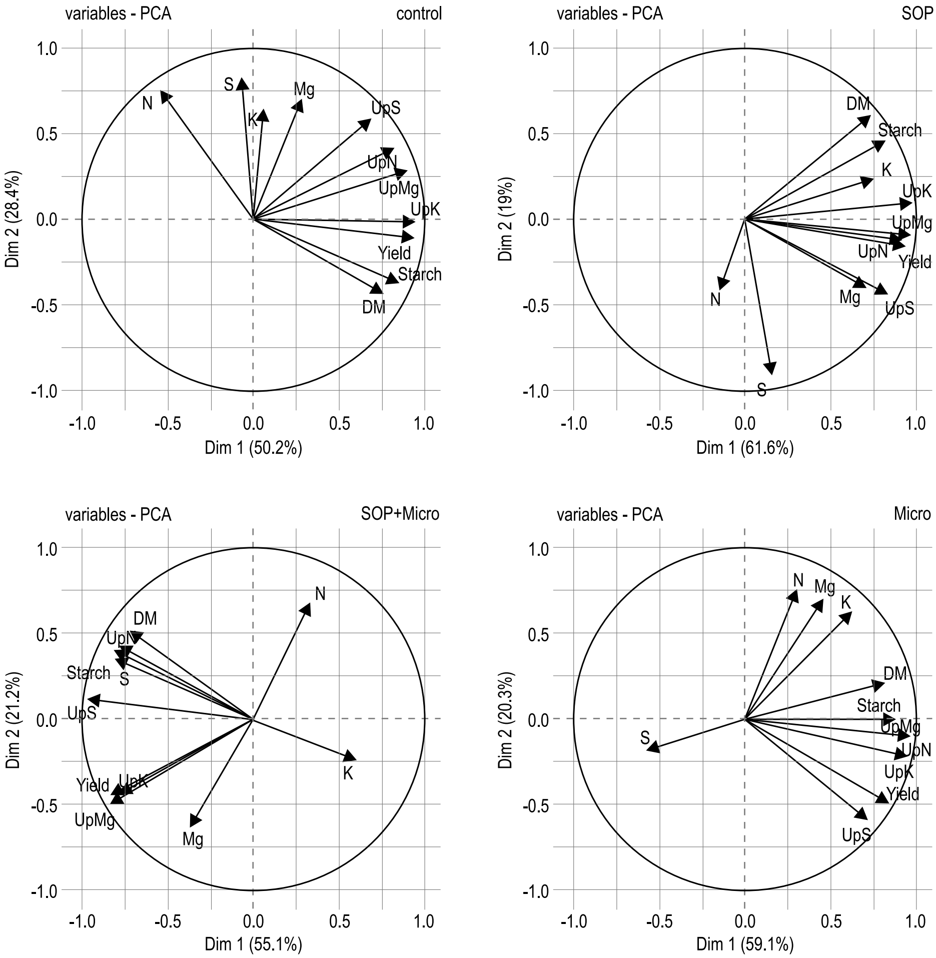

Fig. 2. Two-dimensional spatial image of variable macroelement accumulation and yield and quality parameters of potato tubers, Zorba variety: N, K, Mg, S – macrolelement content, UpN, UpK, UpS, UpMg – macroelement uptake, DM – dry matter

in tubers and their accumulation did not affect the starch content in the Hermes variety. In the Zorba variety, the accumulation of element in tubers determined the potato protein content in 50%.

Nutrient uptake per crop unit

The specific rate of nutrient uptake provides information on nutrient amount per unit of harvested yield. The primary task of a potato grower is to optimise nutrient management (especially fertilisers and nitrogen in the soil) so that the specific uptake of a given nutrient is reduced while obtaining a high yield of high technological quality. Achieving this goal is possible under conditions of proper nutrition with all elements. The crisps variety was found to have higher values of unit uptake of the elements analysed than the French fries variety had (Table 6). The unit uptake of nitrogen for the Zorba variety ranged from 1.97 kg N to 2.93 kg N t^{-1}, while for the Hermes variety it varied between 2.90 and 3.94 kg N t^{-1}. When comparing the values of indices of the unit uptake obtained in our research with literature data, the former were much lower. According to literature data (SILVA et al. 2018), the potato needs for nitrogen and potassium, assuming high tuber production (over 55 t ha^{-1}), are as follows: 5.3 kg of N and 6.64 kg of K.

In our experiment, regardless of the year of study, the experimental factor significantly differentiated the value of unit uptake of potassium only in the case of the French fries (Zorba) variety. For the Hermes variety, the average values of the index of the unit potassium uptake ranged from 3.42 to 4.02 kg t^{-1}, while lower values were noted for the Zorba variety and were contained in the range of 2.68 to 3.78 kg N t^{-1}. The synthesis of results from three years of research showed that, compared to the control object, foliar fertilisation with potassium and micronutrients significantly increased the K_{unit} index only for the Hermes variety.

However, no statistically significant differences were found between the treatments analysed. For the other variety tested (Zorba), the synthesis

Table 6

Effect of the experimental factor on the unit macroelement uptake by potato tubers (kg t^{-1})

Years	Treatments	Potato varieties							
		Zorba				Hermes			
		N	K	Mg	S	N	K	Mg	S
2014	control	2.93*a*	3.06*ab*	0.165*a*	0.503*a*	3.56*a*	3.66*a*	0.201*a*	0.574*a*
	SOP	2.43*ab*	2.68*b*	0.139*b*	0.389*a*	3.71*a*	4.02*a*	0.210*a*	0.572*a*
	SOP+Micro	2.43*ab*	3.38*a*	0.171*a*	0.406*a*	2.93*a*	3.75*a*	0.188*a*	0.564*a*
	Micro	1.97*b*	2.83*b*	0.134*b*	0.365*a*	3.55*a*	3.75*a*	0.205*a*	0.492*a*
2015	control	2.73*a*	3.25*ab*	0.141*ab*	0.301*a*	3.94*a*	3.36*a*	0.176*a*	0.489*ab*
	SOP	2.57*a*	3.13*b*	0.134*b*	0.292*a*	3.54*a*	3.85*a*	0.204*a*	0.449*ab*
	SOP+Micro	2.70*a*	3.21*ab*	0.135*b*	0.316*a*	3.45*a*	3.68*a*	0.176*a*	0.566*a*
	Micro	2.93*a*	3.45*a*	0.171*a*	0.430*a*	3.57*a*	3.78*a*	0.193*a*	0.416*b*
2016	control	2.16*b*	3.06*b*	0.163*a*	0.366*a*	2.88*a*	3.42*a*	0.196*a*	0.574*a*
	SOP	2.65*ab*	3.70*a*	0.176*a*	0.394*a*	2.79*a*	3.88*ab*	0.210*a*	0.572*a*
	SOP+Micro	2.33*ab*	3.46*ab*	0.148*a*	0.322*a*	2.93*a*	4.02*a*	0.228*a*	0.564*a*
	Micro	2.79*a*	3.78*a*	0.181*a*	0.364*a*	3.12*a*	3.82*ab*	0.217*a*	0.492*a*
Mean 2014--2016	control	2.63*a*	3.12*a*	0.156*a*	0.390*a*	3.46*a*	3.48*b*	0.191*a*	0.483*a*
	SOP	2.55*a*	3.17*a*	0.150*a*	0.355*a*	3.35*a*	3.90*a*	0.208*a*	0.497*a*
	SOP+Micro	2.52*a*	3.34*a*	0.152*a*	0.363*a*	3.11*a*	3.82*a*	0.197*a*	0.541*a*
	Micro	2.56*a*	3.36*a*	0.162*a*	0.386*a*	3.41*a*	3.81*a*	0.205*a*	0.454*a*

* Values in the same column followed by the same letter indicate a lack of significant differences within the treatment. Tukey's test ($p<0.05$).

of the results from three years of the study showed only an increasing trend for K_{unit} uptake consistently with the foliar sprays applied. Potassium is a mineral nutrient with the largest demand for potatoes, with about 4.4 kg K removed per 1000 kg of tubers, and proper potassium management is extremely important for sustaining high tuber yield and quality (Alva et al. 2011, Zorb et al. 2014). Oosterhuis et al. (2014) indicate that high levels of potassium accumulation in tubers could be due to the active involvement of K in carbon fixation, respiration, synthesis of amino acids and unloading of photo-assimilates in short-sand, long-distance transport. Research by Klikocka (2015) proved that there was no variation by years in the K content in the dry tuber mass, but K uptake in the dry mass of tubers was dependent on the growing season. According to Kang et al. (2014), potato crop took up more K than it required when the K availability was high.

According to the above authors, it is recommended that K fertilisation of potatoes calculated corresponding to the K_{unit} uptake should account for the variability of production conditions, because higher values of unit uptake may result from growing plants on sites with high potable potassium content, which contributes to its luxurious uptake. In the case of sulphur for the Zorba variety and magnesium for the Hermes variety, the analysis of variance showed no significant relationships between the treatments analysed (Table 6). The values of unit uptake of sulphur ranged from 0.30 to 0.5 kg S t^{-1} (Zorba) and from 0.4 to 0.57 kg S t^{-1} (Hermes), while these of magnesium 0.14-0.18 kg Mg t^{-1} and 0.17-0.23 kg Mg t^{-1}, respectively.

CONCLUSION

The effect of the experimental factor on the tuber content of macroelements varied from year to year. Two-fold application of potassium sulphate and microelements, regardless of the growing season, increased the accumulation of potassium in tubers of both varieties. The impact of foliar treatments on the accumulation of other nutrients in tubers was not unequivocal and was largely conditioned by the course of weather conditions during the growing season. Regardless of the experimental treatment, the yield responses of both potato varieties were influenced by the tuber macroelement accumulation in 67-87%, while the protein content in 63-69%.

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