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MINERAL DENSITY OF ONION BULBS AS AFFECTED BY FERTILIZERS BASED ON ELEMENTAL SULFUR

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Abstract

The yield increase of vegetables, including common onion (*Alium cepa* L.), is of great interest to growers. However, higher yield often leads to what is known as *genetic dilution* of mineral density. A technology of onion fertilization based on elemental sulfur (S^0) fertilizers seems to be a simple agronomic measure preventing a decrease in the nutrient concentration in onion bulbs. To verify this hypothesis, field studies were conducted in the 2009 and 2010 seasons. A two-factorial trial consisted of five sulfur fertilizers: S_w (crude form of S^0), S_m (micronized S^0), S_{mCu} (S_m enriched with copper 0.25%), S_{mZn} (S_m enriched with zinc 0.5%), and AS (ammonium sulfate); and, as the second factor, of two doses of S: 30 and 60 kg ha^{-1}. The NPK plot, included as an independent experimental variant, was used as the control. Yield of onion increased by 13% in response to 30 kg S ha^{-1}, and by 44% when fertilized with 60 kg S ha^{-1}. The yield of bulbs was significantly affected by increasing magnesium and negatively by sodium concentration. The increase in both bulb yields and dry matter content resulted in a simultaneous decrease in nutrient density, except sulfur. The strongest dilution effect was observed for sodium (-33%), iron (-19%), magnesium (-17%) and phosphorus (-16%). Such a negative development can be prevented by applying sulfur fertilizers in an appropriate form. The concentrations of N, P, K, N, and Cu responded most demonstrably to the added ammonium sulfate. The concentrations of S, Zn, Cu, Mn, and Fe were affected by the micronized form of S^0 enriched with zinc. The magnesium concentration was the highest in plants fertilized with the crude form of S^0.

Keywords: yield of bulbs, nutrient density, sulfur fertilizers.

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INTRODUCTION

Onion (*Alium cepa* L.) is one of the most important vegetable crops cultivated worldwide. The total harvested area of dry onion in 2011-2013 was 43 million ha. The average yield was approximately 20 t ha^{-1}. The key producers are China, India, the USA, Pakistan, and Turkey. In Europe, the leading producers are Russia, the Netherlands, Spain, Poland and Germany. The harvested yields in Poland are half the ones achieved in Germany, i.e. 20-25 t ha^{-1} versus 45-50 t ha^{-1} (FAOSTAT 2015).

Nowadays, the most severe problem in vegetable production is the significant decline in mineral nutrient density in vegetables. This process has been widely recognized in the USA and in the United Kingdom. In an intensive review concerning vegetables cultivated in England in 1930-1980, Davis (2009) showed a huge decrease in the concentration of copper and a slight decline of iron. The same negative trends were observed for magnesium and calcium. Thomas (2007) reported that the concentrations of copper, calcium and magnesium in vegetables in England decreased by 76%, 40% and 24%, respectively, over a time period spanning the years 1940 and 1992. Such a substantial decrease in element concentrations in edible parts of vegetables is triggered by intensive farming based on high-yielding varieties of crops, which require high doses of key fertilizers, mostly nitrogen. Therefore, this type of nutrient concentration dilution has been termed *genetic dilution* (Davis 2009).

The genetically induced dilution of mineral density can be controlled, relying on a number of plant cultivation properties. The most important are the ones arising from plant breeding progress and agronomic measures, referred to as bio-fortification (White, Broadlaey 2005). The unfavourable process of nutrient dilution, responsible for deteriorated food quality, can be easily halted by applying micronutrients, such as copper and especially zinc, to plantations. There are numerous methods of macro- and micronutrient application, of which the most frequent one is foliar fertilization (Trivedi, Dumal 2013).

Onion consumption continues to grow, stimulated by our knowledge of the chemical composition of this vegetable, which in many ways is beneficial to the human health (Griffits et al. 2002). The key indicators of onion health-promoting benefits are sulfur derivative compounds. Therefore, pure sulfur (S^0), acting as a micronutrient carrier, seems to be the simplest agronomic agent for attaining an improved quality of onion bulbs. Elemental sulfur added to soil undergoes oxidation, in turn leading to the release of plant available sulfur and increasing the rate of soil organic mineralization, as documented by a higher content of ammonium nitrogen (Skwierawska et al. 2008). This process also causes local soil acidification (Turan et al. 2013). Thus, it has been assumed that a local decrease of soil pH results in a higher availability of micronutrients for growing crops.

The key objective of this experiment has been to evaluate the effect of onion biofortification with minerals based on elemental sulfur applied alone or enriched with microelements such as copper and zinc.

MATERIAL AND METHODS

A study on the mineral status of onions at harvest was carried out during two growing seasons, in 2009 and in 2010, at Szemborowo (52°21′N; 17°43′E), Poland. A field experiment was established on soil originating from sandy loam, classified as Albic Luvisol. Soil fertility as indicated by the main agrochemical characteristics was satisfactory for producing high yield of bulbs (Table 1). The study was based on two factorial trials, consisting of:

Table 1

Agrochemical characteristics of soils before sowing and at harvest*, 0-30 soil layer

Soil characteristic	2009		2010	
	before sowing	at harvest	before sowing	at harvest
pH	6.4	6.3	5.9	6.0
P as P_2O_5 (mg kg^{-1})	192	83	188	100
K as K_2O (mg kg^{-1})	250	167	330	180
Mg (mg kg^{-1})	91	58	101	67
Zn (mg kg^{-1})	8.4	3.2	6.5	4.1
Cu (mg kg^{-1})	6.2	4.1	9.2	6.1
N_{min} (kg ha^{-1})	70	64	59	65
S* as S-SO_4 (kg ha^{-1})	3.3	12.1	4.1	9.2

* the S_w treatment fertilized with 60 kg S ha^{-1}

1) five sulfur fertilizers, including four based on elemental sulfur (S^0) : S_w (crude form of S^0), S_m (micronized S^0), S_{mCu} (S_m enriched with copper 0,25%), S_{mZn} (S_m enriched with zinc 0,5%), and AS (ammonium sulfate);
2) two doses of applied S: 30 and 60 kg S ha^{-1}.

The control treatment, fertilized with NPK, was considered as an independent experimental variant. All treatments were replicated four times. The total size of a single plot was 48 m^2. The onion variety *Supra* was sown in the second decade of April. Onion plants were harvested in the first decade of September from an area of 12 m^2.

Phosphorus as triple superphosphate and potassium (muriate of potash 60% K_2O) was applied in autumn in doses adjusted to the soil test class. Nitrogen (ammonium saltpeter, 34.0 % N) was dressed at a dose of 120 kg N ha^{-1} before sowing. Sulfur was applied in accordance with the treatment schedule three weeks before onion sowing.

Plant material for dry mater yield and nutrient concentration determinations was sampled at the onion's physiological maturity. Nitrogen concentration was determined by the standard macro-Kjeldahl procedure. Plant material for other nutrients was ashed at 600°C and next dissolved in 33% HNO_3. Phosphorus concentration was determined by the vanadium-molybdenum method and measured using a Specord 2XX/40 at 436 nm wave; potassium and calcium were detected by flame-photometry while magnesium and micronutrients were analysed by atomic-absorption spectrometry – the flame type. For total sulfur determination, the turbidometric method was used (Bardsley, Lancaster 1980). All results are expressed on a dry matter (DM) basis. Nutrient accumulation was calculated by the multiplication of a nutrient concentration and yield obtained per area.

The data originating from the field experiment were subjected to conventional analysis of variance using a computer programme package Statistica® 10. Differences between the treatments were evaluated with the Tukey's test. The tables and figures contain results from the *F* test (***, **, * indicate significance at the $p < 0.1\%$, 1%, and 5%, respectively). Stepwise regression was applied to define an optimal set of variables for a given crop characteristic. In the computing procedure, a consecutive variable was added to multiple linear regressions in a step-by-step manner. The best regression model was chosen based on the highest *F*-value for the entire model and significance of all independent variables (Konys, Wiśniewski 1984).

RESULTS AND DISCUSSION

Yield of bulbs

Onion as a vegetable crop is highly sensitive to the course of weather. This assumption has been fully corroborated in the study. Yield of bulbs showed a response to the interaction of all factors, including the plant growing seasons. Slightly higher yields were recorded in 2010 with high precipitations in summer months. Despite the recorded year-to-year variability, the harvested yields responded significantly to the dose and composition of sulfur fertilizers (Figure 1). Plants fertilized with NPK yielded at the level of 36.3 t ha^{-1}, which is significantly higher than the country's average, but lower compared to the average yields harvested in Germany or in the Netherlands (FAOSTAT 2015). The response of harvested yields depended on the chemical composition of the fertilizers and S doses. In general, plants fertilized with 30 kg S ha^{-1} increased the yield of bulbs, except the plot with crude sulfur. There, much higher yield variability was observed in treatments fertilized with 60 kg S ha^{-1}. The yield of bulbs decreased in the order:

$$S_w \geq S_m > S_{mCu} = S_{mZn} > AS$$

The response of onion to added sulfur was much stronger in plants fertilized with elemental sulfur compared to ammonium sulfate. However, the yield increase was significantly modified by the applied dose of sulfur. Plants

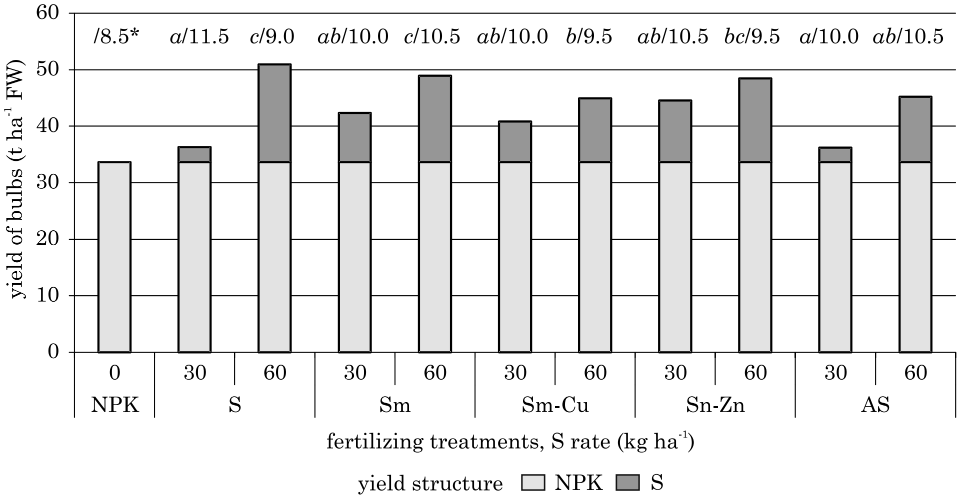


Fig. 1. The effect of sulfur based fertilizers and sulfur does against the background of NPK on yield of bulbs, mean for 2009-2010: 8.5* – dry matter content (%), ^{a} – the same letter means a lack of significant differences

fertilized with 60 kg S ha^{-1} produced on average 44% higher yield of bulbs, whereas those fertilized with 30 kg S ha^{-1} increased only by 13%. The response of onion's dry matter content to the tested S fertilizers needs to be emphasized. Generally, any of the applied fertilizers resulted in an increase of the dry matter of onion bulbs compared to those which received only NPK. On average, the highest increase was noted for plants fertilized with ammonium sulfur and micronized elemental sulfur. The result implicitly underlines the high sensitivity of onion to sulfur supply. This conclusion agrees with the data reported by Mishou et al. (2013) for Malaysia and by Skwierawska et al. (2008) for Poland. The former team of researchers recommend sulfur in a dose of 40 kg S ha^{-1} as optimal on soils with pH of 6.5, whereas the Polish scientists suggest a range between 60 to 80 kg S ha^{-1}. The observed differences in the impact of S doses on oinon yield were most evident in 2009. In 2010, yield increase did not appear in treatments with micronized S, applied alone or with copper. The highest year-to-year variability of harvested yields was noted for the treatment with zinc. The importance of this element for onion was documented by Trivedi and Dumal (2013), who showed that foliar application of zinc, irrespective of the type of fertilizer, i.e., mineral or manure basic fertilizers, resulted in a yield and bulb grade increase. The significant impact of S fertilizers based on elemental sulfur on yield of bulbs can be attributed to two factors. Firstly, the initial content of soil S-SO_4 was low: 4.0 in 2009 and 3.0 mg kg^{-1} in 2010. Secondly, the observed effects of elemental sulfur can be explained by its oxidation, resulting in the acceleration of numerous soil processes, responsible for nutrient supply to growing plants, as recently reported for maize by Karizimarchi et al. (2014).

Nutrient concentration

Nutrient concentration in bulbs responded to the course of weather, but significant differences were recorded only for N, S, Mg, Zn and Fe (Table 2). In the case of N and Mg, their concentrations were higher in the wet season of 2010. A reverse response was noted for S and both micronutrients. The effect of S fertilizers was recorded for all nutrients except calcium.

A significant impact of sulfur fertilizer and its dose on sulfur concentration in bulbs was found (Figure 2). The effects were evoked mostly by the

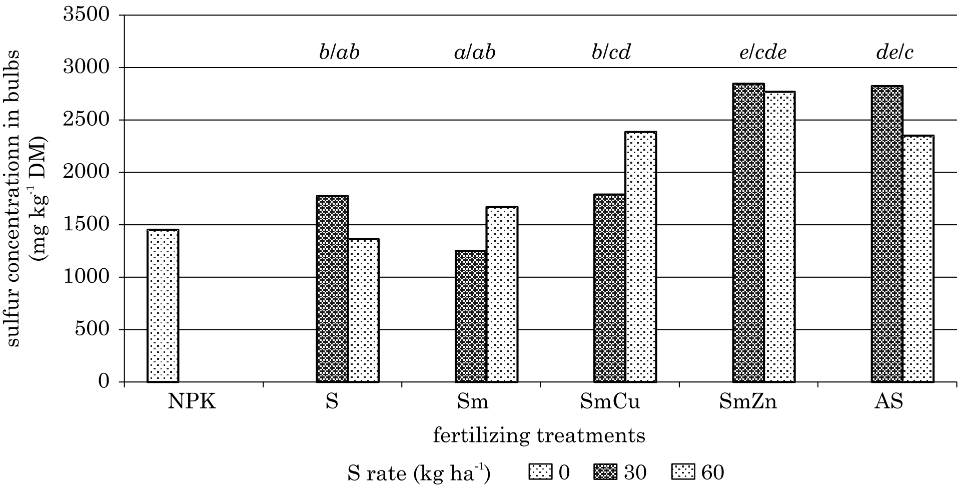


Fig. 2. Effect of sulfur fertilizer composition and its dose on sulfur concentration in onion Bulbs: [a] – the same letter means a lack of significant differences

added micronutrients, as observed for zinc. Its addition resulted in a double S concentration, irrespective of the S dose. This finding is in agreement with the data reported by TRIVEDI and DUMAL (2013), who showed a significant impact of zinc fertilizer on the yield of onion. A high increase, but much lower compared to zinc, was noted for ammonium sulfate. The concentration of six out of the eleven nutrients, namely N, P, K, S, Na, and Cu, was significantly affected by ammonium sulfate. The highest magnesium concentration was recorded in plants fertilized with the crude form of S^0. Zinc concentration responded significantly to the micronized S^0 fertilizer supplemented with zinc. This fertilizer also affected positively the concentration of manganese and iron. The effect of sulfur doses on nutrient concentration was observed only for N, P, Mg, and Fe. For the first three nutrients, a significant decrease was recorded in response to the higher S dose. This trend, although not statistically confirmed, was also observed for the other nutrients except sulfur and magnesium. Concomitant with an increase in the yield of bulb, the trend indicates the *dilution effect* due to the application of sulfur.

The recorded data on the response of single nutrient concentrations to sulfur fertilizers was compared with the analogous concentrations in bulbs

Table 2

Nutrient concentration in onion bulbs at harvest

Factor	Factor level	Macronutrients (g kg^{-1} DM)							Micronutrients (mg kg^{-1} DM)			
		N	P	K	S	Ca	Mg	Na	Zn	Cu	Mn	Fe
Fertilizer (*F*)	S^o	17.6^{ab}	3.4^{ab}	16.2^{ab}	1.6^{a}	14.1	2.6^{b}	1.3^{ab}	13.0^{a}	5.7^{a}	17.2^{bc}	66.8^{a}
	S^o_m	17.7^{ab}	3.4^{ab}	14.6^{a}	1.5^{a}	13.1	2.1^{a}	1.4^{ab}	13.1^{a}	5.8^{a}	16.2^{ab}	96.6^{b}
	S^o_{mCu}	20.0^{bc}	3.2^{a}	17.4^{b}	2.1^{b}	11.4	2.1^{a}	1.1^{a}	13.5^{a}	5.7^{a}	18.2^{b}	63.4^{a}
	S^o_{mZn}	17.2^{a}	3.3^{a}	18.2^{c}	2.8^{c}	12.9	2.2^{a}	1.6^{b}	16.5^{b}	5.9^{ab}	18.1^{b}	90.5^{b}
	AS	21.5^{c}	3.7^{b}	18.2^{c}	2.6^{c}	12.7	2.3^{a}	1.5^{b}	15.1^{ab}	6.4^{b}	15.7^{a}	71.3^{a}
Dose (kg ha^{-1}) (*R*)	30	19.5^{a}	3.5^{b}	17.2	2.1	12.9	2.2	1.4^{b}	14.4	5.6	17.4	75.0^{a}
	60	18.1^{a}	3.2^{a}	16.7	2.1	12.7	2.3	1.3^{a}	14.0	5.4	16.8	80.5^{b}
Year (*Y*)	2009	18.0^{a}	3.4	17.2	2.2^{b}	12.5	2.2^{a}	1.4	14.7^{b}	5.6	17.5	81.0^{b}
	2010	19.6^{b}	3.3	16.7	2.0^{a}	13.1	2.3^{b}	1.3	13.7^{a}	5.4	16.7	74.4^{a}
Source of variance												
Y x *F*		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Y x *R*		**	***	n.s.	n.s	n.s.	n.s.	n.s.	***	n.s.	***	n.s.
R x *F*		n.s.	n.s.	n.s.	***	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.
Y x *R* x *F*		n.s.	n.s.	n.s.	n.s.	n.s.	***	n.s.	n.s.	n.s.	n.s.	n.s.
NPK – control		20.0	4.1	18.7	1.5	13.5	2.7	2.0	16.2	6.0	17.2	96.4

* significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, n.s. – not significant, [a] the same letter means a lack of significant differences

fertilized with NPK, considered as the quantitative and qualitative control. On average, the concentration of all nutrients, except sulfur, decreased. The descending order of nutrients is as follows:

$$Na\ (-33\%) > Fe\ (-19\%) > Mg\ (-17\%) \geq P\ (-16\%) > Zn\ (-12\%) \geq N\ (-11\%) \geq K\ (-10\%) \geq Cu\ (-9\%) > Ca\ (-5\%) > Mn\ (-1\%).$$

The data, excluding nitrogen and sulfur, were additionally compared with the threshold values, considered as standards in Finland (Ekholm et al. 2007) and in the United Kingdom. Nitrogen concentration strongly responded to the type of S fertilizer, decreasing in most treatments except S^{o}_{mCu}. Plants fertilized with ammonium sulfate showed higher values compared to the control. Phosphorus concentration in bulbs, irrespective of the applied S fertilizer, was lower. In treatments with added micronutrients, its concentration decreased by 20-22%. The lowest value of 3.2 mg kg^{-1} DM was still higher than the threshold values in Finland and the UK. The same relationship was noted for potassium. The concentration of potassium in bulbs fertilized with the S^{o}_{m} fertilizer was also 22% lower than the control. This value was also below the threshold values in Finland and the UK. Sulfur concentration in bulbs showed a strong, positive response to S fertilizer enriched with micronutrients and to ammonium sulfate. Calcium concentration, ranging from 11.4 to 14.1 g kg^{-1} DM, was less than the threshold values in Finland and equaled half the UK standard value.

Concentrations of magnesium and sodium require special attention. Regarding magnesium, its concentration showed significant sensitivity to all the factors, including the plant growing season. Magnesium concentration in plants fertilized only with pure sulfur responded to the S dose, irrespective on the characteristics of the season. A reverse response was observed in plants treated with micronized S enriched with zinc or fertilized with ammonium sulfate. The seasonal effect was revealed in plants fertilized with micronized S enriched with copper. In 2009, magnesium concentration decreased in response to the applied S dose, while increasing in the subsequent year under the influence of the same type of fertilization (data not shown but available from the authors). Magnesium concentration in the standard onion bulb in Finland is estimated at the level of 0.85 mg kg^{-1} DM, whereas in the UK it is expected to be 0.4 mg kg^{-1} DM. The current study showed several -fold higher values. Sodium concentration did not show any response to the experimental factors and seasons. Its concentration in bulbs of the NPK treated plants was 2.0 g kg^{-1}, being seven-fold higher than the threshold in the UK.

Micronutrients are the third group of minerals broadly used for nutritional status assessment in onion bulbs (Mayer 1997). Zinc concentration in plants fertilized with NPK amounted to 16.2 mg kg^{-1} DM. This value was higher compared to bulbs treated with zinc. In the other cases, it was even lower by 20%. This level of Zn concentration is considered as the Zn threshold in Finland. Values determined by Jurgiel-Małecka and Suchorska-Orłowska (2008) are twice as high. These authors, however, showed that zinc concentration strongly decreased in response to an increasing dose of fertilizer nitrogen. Copper concentration of 6.4 mg kg^{-1} DM in the AS treatment was slightly higher compared to its concentration in the NPK bulbs. It decreased significantly parallel to the increasing yield of bulbs. Jurgiel-Małecka and Suchorska-Orłowska (2008) reported that Cu concentration was highly responsive to nitrogen doses but not to the N source. The value they cited was also by 50% higher than the Finnish standard and only slightly above the UK norm. Manganese concentration showed strong sensitivity to the interaction of year and fertilizer dose. In both years, its concentration was significantly lower in plants fertilized with 60 kg S in the form of S^{o}_{m} enriched with Cu or zinc. The values were much above the threshold value in Finland. Iron concentration responded only to the fertilizing treatments, peaking in the S^{o}_{mZn} fertilized plants. It was, however, low compared to 96 mg kg^{-1} DM for bulbs from the NPK plot. This value is 2- and 3-fold lower than the Finnish and British thresholds, respectively. Jurgiel-Małecka and Suchorska-Orłowska's (2008) results are even lower.

The relationships among nutrients were significant only for some pairs of nutrients (Table 3). Sulfur concentration significantly affected the concentration of potassium, zinc and copper. The latter nutrient, as reported by Davis (2009), showed the highest dilution effect in response to increasing yields of vegetables in the United Kingdom in 1930-1980. Therefore, application of sulfur fertilizers to the onion crop can be thought of as a simple agronomic treatment, which improves the mineral composition of bulbs. The re-

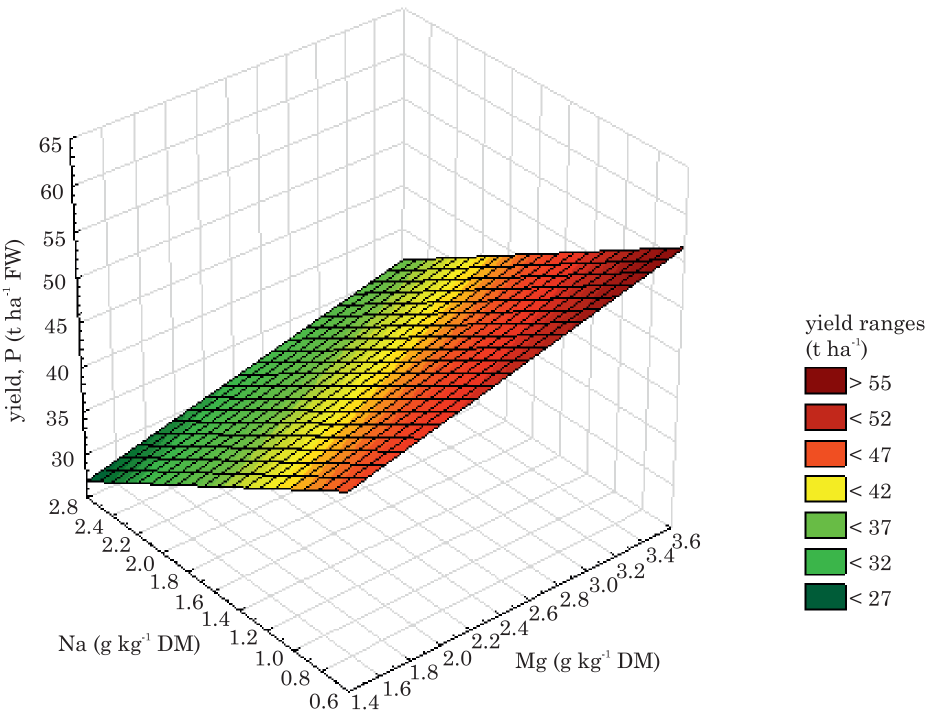
Table 3

Matrix of correlations for nutrient concentration and yield in all the samples, $n = 66$

Nutrients	K	P	S	Ca	Mg	Na	Zn	Cu	Mn	Fe	Yield
N	0.32**	0.27*	-0.09	0.06	0.12	0.03	0.02	0.32**	-0.06	-0.27*	-0.02
K	1.00	0.16	0.34**	-0.00	0.05	0.30**	0.27**	0.48***	-0.01	-0.07	-0.18
P		1.00	-0.15	0.02	0.17	0.47***	0.05	0.25*	-0.11	-0.01	-0.39**
S			1.00	-0.11	-0.21	-0.04	0.47***	0.29*	0.03	0.01	-0.05
Ca				1.00	0.13	0.11	-0.14	0.02	-0.18	0.12	0.16
Mg					1.00	0.16	-0.14	0.30*	0.12	0.04	0.15
Na						1.00	0.42**	0.19	0.03	0.28*	-0.44**
Zn							1.00	0.19	0.08	0.26*	-0.31*
Cu								1.00	0.11	-0.33**	-0.14
Mn									1.00	-0.01	-0.20
Fe										1.00	0.06

* significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, n.s. – not significant

lationship between a given nutrient and yield was significant for the uptake of phosphorus, sodium and zinc. In addition, sodium was significantly correlated with both the other nutrients and with potassium and iron. The stepwise regression procedure applied implicitly showed that magnesium and sodium were two nutrients that played a decisive role shaping the yield of bulbs. As seen in Figure 3, these two nutrients showed significant, antagonistic impact



$$Y = 47.11 + 4.294Mg - 10.09Na$$

Fig. 3. Yield of onion bulbs as a function of the interaction between magnesium and sodium concentrations, n = 66, R^2 = 0.38

on yield. The highest yield was obtained when high concentration of magnesium and low concentration of sodium were ensured. This relationship, simultaneous with the level of magnesium concentration in bulbs, stresses the importance of this nutrient as a critical one for both yield and nutritional quality of onion. It corroborates the concept that a higher yield of crops of good quality can be secured provided an adequate Mg supply during the time of yield formation (Grzebisz et al. 2010, Grzebisz 2013, Rosanoff 2013).

Nutrient accumulation

High variation in nutrient accumulation in onion bulbs has been observed (Table 4). Six of the eleven nutrients, namely N, Ca, Mg, Na, Zn, and Mn, responded significantly to the changeable course of the weather. All

Table 4

Nutrient accumulation in onion bulbs at harvest

Factor	Factor level	Macronutrients (kg ha^{-1} DM)							Micronutrients (g ha^{-1} DM)			
		N	P	K	S	Ca	Mg	Na	Zn	Cu	Mn	Fe
Fertilizer (*F*)	S^o	77.4^{ab}	15.0^{ab}	71.3	6.85^{a}	61.7^{b}	11.5^{b}	5.80^{ab}	557.0^{a}	251.8^{ab}	757.1^{ab}	2934^{a}
	S^o_m	79.8^{ab}	15.5^{ab}	67.6	6.87^{a}	59.3^{ab}	9.9^{ab}	6.30^{a}	603.4^{b}	171.2^{a}	737.3^{ab}	3972^{b}
	S^o_{mCu}	82.0^{ab}	13.0^{a}	71.5	8.57^{a}	46.6^{a}	8.6^{a}	4.36^{b}	580.3^{ab}	244.7^{ab}	777.5^{b}	2711^{a}
	S^o_{mZn}	73.4^{a}	14.0^{ab}	78.3	12.0^{b}	55.6^{ab}	9.6^{ab}	6.58^{a}	714.3^{c}	257.3^{ab}	774.9^{b}	3972^{b}
	AS	96.1^{b}	16.2^{b}	80.6	11.5^{b}	56.3^{ab}	10.0^{ab}	6.53^{a}	615.4^{bc}	260.7^{b}	647.4^{a}	2943^{a}
Dose (kg ha^{-1}) (*R*)	30	83.3	15.1	73.6	9.00	54.8	9.4^{a}	6.09	586.5^{a}	228.1	704.5^{a}	3061^{a}
	60	80.1	14.4	74.2	9.30	57.0	10.4^{b}	5.77	641.6^{b}	246.4	773.2^{b}	3736^{b}
Year (*Y*)	2009	74.8^{a}	14.4	71.7	9.24	51.7^{a}	9.1^{a}	5.72^{a}	592.7^{a}	222.2	694.4^{a}	3354
	2010	88.7^{b}	15.1	76.1	9.06	60.2^{b}	10.8^{b}	6.15^{b}	628.4^{b}	247.9	759.5^{b}	3445
Source of variation												
Y x *F*		n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	**	*	n.s.	n.s.
Y x *R*		n.s.	**	n.s.	n.s	n.s.	n.s.	n.s.	*	*	**	n.s.
R x *F*		n.s.	n.s.	n.s.	***	n.s.	***	n.s.	**	n.s.	*	*
Y x *R* x *F*		n.s.	n.s.	n.s.	*	n.s.	*	n.s.	*	n.s.	n.s.	n.s.
NPK – control		64.1	4.38	56.5	12.1	41.4	6.0	8.2	575.4	213.0	607.9	3409

* significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, n.s. – not significant, [a] the same letter means a lack of significant differences

these elements accumulated more efficiently in the wet 2010. A remarkable increase in the response to the dose of sulfur was recorded for Mg, Zn, Mn, and Fe. Potassium was the only element that did not respond to the applied fertilizers. The highest amount of nitrogen was recorded in bulbs of plants fertilized with ammonium sulfate, where it was ½ higher compared to the NPK treatment and $^1/_3$ higher than in the treatment with S^o_{mZn}. An increase was found in the quantity of phosphorus in bulbs that corresponded to specific types of S fertilizers. The highest accumulation again was the attribute of plants fertilized with ammonium sulfate. The amount of S in bulbs was highly differentiated due to the interactional effect of all treatments. As shown in Figure 4, the course of S accumulation was similar in both years. The highest dynamics occurred in treatments with S_{mZn} and ammonium sulfate. In 2009, these two treatments showed the maximum amount of accumulated S, irrespective of the S dose. In 2010, the S dose of 60 kg S ha^{-1} resulted in an accumulation decline accompanied by an increase in the yield of bulbs. The importance of elemental form of S in onion production is highlighted worldwide, regardless of specific growing conditions, as reported by MISHU et al. (2013) in Bangladesh or by AVAD et al. (2011) in Egypt. In our study, the impact of applied S on its accumulation in bulbs was enhanced by the added micronutrients or by nitrogen in the ammonium form. Accumulation of calcium in bulbs was the highest in treatments fertilized with S^0. Any added micronutrient, especially copper, caused a decrease in the calcium accumulation.

Magnesium deserves special attention. Its accumulation in onion bulbs showed a significant dependence on interaction of all factors, including the season (Figure 5). On average, the highest S was the attribute of the S_w treatment, followed by the AS. In the first case, the amount of S increased, ir-

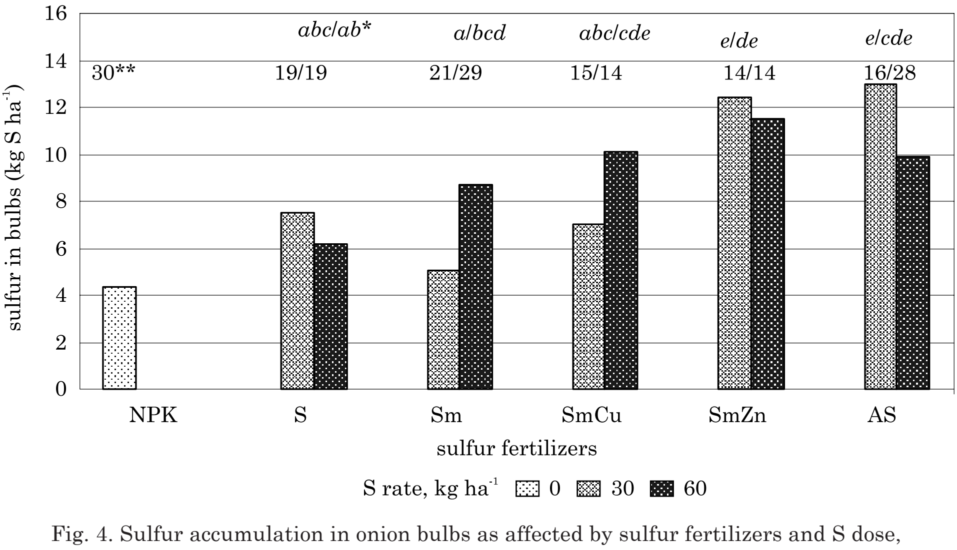


Fig. 4. Sulfur accumulation in onion bulbs as affected by sulfur fertilizers and S dose, means for 2009-2010: * S dose of 30 and 60 kg ha^{-1}, respectively, ** coefficient of variation (%), ^{a} – the same letter means a lack of significant differences

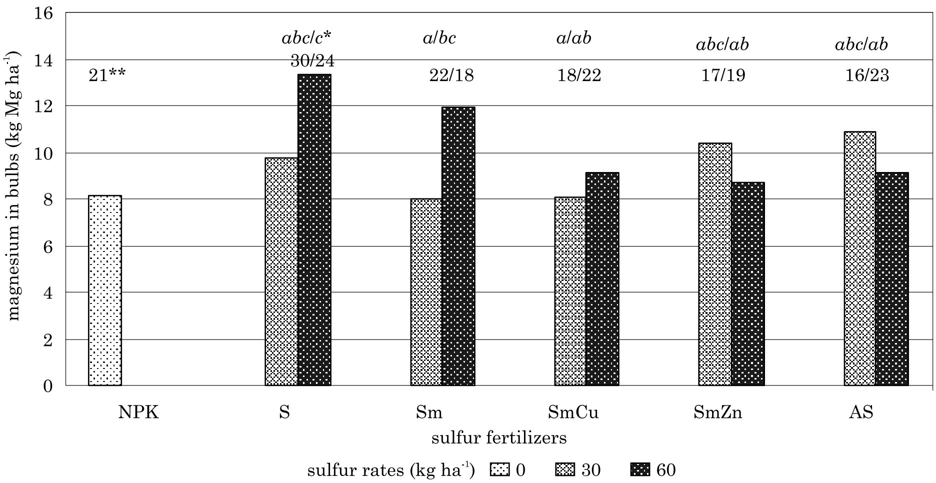


Fig. 5. Magnesium accumulation in onion bulbs as affected by sulfur fertilizers and S dose, means for 2009-2010: * S dose of 30 and 60 kg ha^{-1}, respectively, ** coefficient of variation (%), [a] – the same letter means a lack of significant differences

respectively on the season, in accordance to the S rate. The same pattern has been observed for plants fertilized with the micronized S^0. In 2009, the amount of S was higher in bulbs fertilized with 60 kg S ha^{-1}, whereas in 2010, it showed an opposite trend.

Among the studied micronutrients, zinc showed the highest sensitivity to experimental factors and vegetation seasons. The impact of sulfur fertilizers on zinc accumulation in bulbs was recorded only in 2010. It was, however, dependent on the type of fertilizer. The significant increase, irrespectively on the S rate, was recorded in treatments with the micronized S^0. The highest increase, as expected, was the attribute of plants fertilized with zinc. The significant effect of ammonium sulfate was limited only to plants treated with the lower rate of sulfur.

The relationships among nutrients were significant for several pairs of elements (Table 5). Sulfur concentration significantly affected concentrations of N, K, P, Ca, Mg, Na and Zn. However, the S uptake by onion did not affect the yield of bulbs. No significant impact was determined for phosphorus or sodium. All the other nutrients produced an important and positive impact on the yield of bulbs. The highest value of the correlation coefficient was calculated for manganese. Nevertheless, the stepwise regression allowed us to distingusih calcium, zinc, and manganese as yield predictors:

$$Y = 1.89 + 0.15Ca + 0.02Zn + 0.03Mn \text{ for } n = 66 \text{ and } R^2 = 0.78.$$

Positive values of all coefficients of the developed regression model implicitly suggest shortage of these nutrients for both the proper growth and yield formation in onion. The results also indicate that more attention should be paid to to manganese as a nutrient of high importance for onion yield.

Table 5

Matrix of correlations for nutrient accumulation and yield in all the samples, n = 66

Nutrients	K	P	S	Ca	Mg	Na	Zn	Cu	Mn	Fe	Yield
N	0.73***	0.60***	0.40**	0.48***	0.55***	0.42***	0.18	0.39**	0.28*	0.03	0.42***
K	1.00	0.66***	0.63***	0.59***	0.60***	0.60***	0.20	0.39**	0.24	0.14	0.40**
P		1.00	0.37**	0.46***	0.61***	0.65***	-0.04	0.17	0.05	0.05	0.22
S			1.00	0.34*	0.28*	0.37**	0.40**	0.29*	0.14	0.13	0.23
Ca				1.00	0.60***	0.49***	0.19	0.26*	0.31*	0.34**	0.53***
Mg					1.00	0.45***	0.10	0.38**	0.44***	0.24	0.53***
Na						1.00	0.09	0.06	-0.05	0.18	0.08
Zn							1.00	0.41**	0.47***	0.57***	0.63***
Cu								1.00	0.50***	0.09	0.53***
Mn									1.00	0.44***	0.79***
Fe										1.00	0.62***

* significant at $p < 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.001$; n.s. – not significant

CONCLUSIONS

Sulfur applied to onion resulted in both a yield increase and nutrient concentration changes. The significant yield increase, up to 44% in the treatments with 60 kg S ha^{-1}, implicitly indicated on shortage of sulfur to onion plants. The increase of both yield of bulbs and dry matter content resulted in decrease in concentration of all nutrients, except sulfur. The strongest dilution effect was observed for sodium (-33%), iron (-19%), magnesium (-17%), and phosphorus (-16%). For the other nutrients it ranged from -1% for manganese to -12% for zinc. It is only a decrease in sodium that can be viewed as a positive outcome due to the negative impact of this element on the yield of bulbs. Overall, the unwanted dilution of the mineral density in onion bulbs can be prevented by applying sulfur fertilizers in an appropriate form. In general, an increase in the S concentration positively influenced the concentrations of nitrogen, potassium, phosphorus, zinc and copper. The concentrations of N, P, K, N, and Cu responded most strongly to the added ammonium sulfate. The concentrations of S, Zn, Cu, Mn, and Fe were affected by the micronized form of S^0 enriched with zinc. The magnesium concentration was the highest in plants fertilized with the crude form of S^0.

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