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ORIGINAL PAPER

ASSESSMENT OF THE EFFECT OF SULPHUR FERTILISATION ON OAT GRAIN YIELD AND MICRONUTRIENT UPTAKE*

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Abstract

A three-year, single-factor, field experiment was conducted on lessive soil (Haplic Luvisols) with low sulphur content. The aim of the experiment was to determine the effect of selected fertilisers containing ionic sulphur (ammonium sulphate(VI) and potassium sulphate(VI)) and elemental sulphur (Wigor S) on grain yield of the Komes cultivar of oat and on its content of micronutrients (Mn, Fe, Zn and Cu) and their uptake. The fertilisers were applied at doses of 20 and 40 kg S ha^{-1}. Although oat is a species with low sulphur requirements, the study confirmed the positive effect of this nutrient on yield. The average difference in grain yield between plants fertilised and not fertilised with sulphur was 7.8%. No significant differences were noted in the effect of the fertilisers tested on yield. For the ionic form of sulphur, no difference in yield was noted between application doses of 20 and 40 kg ha^{-1}. Application of this nutrient had a significant effect on the manganese and copper content in the oat grain and on the uptake of all micronutrients tested. Of all the fertilisers tested, ammonium sulphate(VI) caused the greatest increase in the content and uptake of all micronutrients except for iron. Application of sulphur, particularly in the form of ammonium sulphate, generally reduced the Fe:Mn ratio. The positive effect of sulphur on yield and its generally positive effect on the content and uptake. of the microelements tested in the oat grain substantiate the need to include this nutrient in cultivation techniques for this species.

Keywords: elemental sulphur, ionic sulphur, micronutrients content, micronutrients uptake, manganese, copper, zinc, iron.

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INTRODUCTION

The sulphur deficiency in Polish soils, which has been worsening in recent years (SIEBIELEC et al. 2012), has risen interest in sulphur as a fertiliser component.

Previous studies on the role of sulphur in determining crop quality indicators have been conducted mainly on plants of the family *Brassicacea*, which have high requirements for this nutrient. There are also reports, however, indicating that cereals and grasses, which take up considerably less sulphur than *Brassicacea*, also respond positively to the presence of this element in fertilisers (GIRMA et al. 2005, BARCZAK 2010, PODLEŚNA 2013, DOSTALOVA et al. 2015, KLIKOCKA et al. 2016).

Few studies have been conducted on the effects of sulphur inclusion in fertilisation of oats. While this species accounts for a small proportion of total crop area (67% – Statistical…2015), it is regarded as one of the most valuable cereals (LANGE 2010, RUXTON, COBB 2015). Recent decades have seen increased interest in non-bread cereals, particularly oats and barley (GAMBUŚ et al. 2006, BUTT et al. 2008). Studies have been conducted on their physicochemical and health-promoting properties, owing to which they can be used for a variety of purposes, in dietetics, medicine or processing (FRIC et al. 2011, ZARZECKA et al. 2015). Oats and oat products exert beneficial effects on human health because they contain protein of the highest biological quality; they are rich in essential unsaturated fatty acids and vitamins (E and B_1, B_2 and B_6). They are also a valuable source of fibre, which is essential in the human diet. Moreover, they have a high content of calcium, magnesium, sodium and copper (LANGE 2010). Among the cereals grown in Poland, oat grain contains the highest amount of ash, composed of macro- and microelements. It has been suggested that applying increased levels of mineral fertilisation, to newer cultivars of oat could have an impact on their grain yield and mineral composition (PISULEWSKA et al. 2009).

To sustain human health, at least 22 biogenic elements must be included a diet (WHITE, BROADLEY 2005), including copper, manganese, zinc and iron (WELCH, GRAHAM 2005). Studies by numerous authors (ARGESANU et al. 2009, KLEIBER, KOMOSA 2011, GAJ et al. 2013) indicate that fertilisation affects concentrations of micronutrients. WANG et al. (2008) suggest that fertilisation with macronutrients, including sulphur, can be used to regulate the content of Cu, Zn, Mo, Ni, and Se, preventing them from accumulating to a toxic level. The available literature contains only a few studies on the effect of sulphur application on the content of micronutrients, which is a very important quality trait in assessment of the nutritional value of the crop (KULCZYCKI 2004, KOZŁOWSKA-STRAWSKA 2009, KLIKOCKA 2011).

Given the progressing sulphur deficiency in Polish soils and the important physiological role of this nutrient in the plant, and in view of the considerable nutritional value of oats, a study was undertaken on this species.

The objective of the research was to evaluate the effect of various fertilisers containing sulphur on the grain yield of oat and its content and uptake of selected micronutrients.

MATERIAL AND METHODS

The study was carried out in 2010-2012 at the Experimental Station of the University of Science and Technology in Wierzchucinek near Bydgoszcz (53°26′ N, 17°79′ E). A field experiment was set up in a randomised block. It was designed as a single-factor experiment. The soil was Haplic Luvisols (IUSS Working Group WRB, 2015) with the textural composition of loamy sand (light soil in the agronomic soil categories). The soil represented very good rye complex, soil valuation class IIIb, with an average content of available forms of phosphorus, magnesium, manganese and iron, and having slightly acidic pH. The content of the sulphate(VI) form S-SO_4^{2-}, as well as that of boron, zinc and copper was low (Table 1). The experiment was performed in triplicate. Plots measured 20 m^2 each and an area for harvest was 16 m^2. Every year, the Komes cultivar of oat was grown after potato as the preceding crop. The experimental factor was the type of mineral fertiliser containing sulphur in the elemental or ionic form. The treatments were as follows: 0, 20 and 40 kg S ha^{-1} in the form of ammonium sulphate(VI), 20 and 40 kg S ha^{-1} in the form of potassium sulphate(VI), and 20 and 40 kg S ha^{-1} in the form of Wigor S fertiliser, containing 90% elemental sulphur and 10% bentonite (Table 2). Agrotechnical procedures were carried out in accordance with recommendations for oat. The mineral fertiliser was applied uniformly before sowing. Nitrogen was applied at a dose of 80 kg N ha^{-1} in the form of ammonium nitrate (on the plots with ammonium sulphate, the amount of ammonium nitrate was reduced accordingly); phosphorus (20 kg P ha^{-1})

Table 1

Content of available forms of macro- and micronutrients of soil (0-25 cm) prior to the plot experiment

	Macronutrients				Micronutrients				
	P-P_2O_5	K-K_2O	Mg-MgO	S-SO_4	Mn	Cu	Zn	Fe	B
(mg kg^{-1})	47.4 (40.2-54.6)	64.5 (53.0-76.0)	29.2 (26.2-32.2)	11.2 (8.2-14.2)	65 (44-86)	1.4 (0.8-2.0)	1.2 (0.9-1.5)	1116 (822-1410)	1.0 (0.54-0.78)
evaluation of richness of soil	average	low	average	low	average	low	low	average	low

Table 2

Fertilisation in the field experiment

Control	Ammonium sulphate (VI) $(NH_4)_2SO_4$		Potassium sulphate (VI) K_2SO_4		Wigor S 90% of elemental sulphur and 10% of bentonite	
(kg S ha^{-1})						
0	20	40	20	40	20	40

was applied in the form of triple superphosphate; and potassium (90 kg K ha^{-1}) was applied as 50% potassium chloride (on the plots with potassium sulphate, the amount of potassium chloride was reduced accordingly).

The region where the field experiment was carried out is characterised by low precipitation levels, at 460 mm a year, with considerable variations in the rainfall between growing seasons. In comparison with the long-term average, the years 2010 and 2011 had relatively high levels of rainfall (Table 3). Much higher precipitation than the long-term average was noted in June and July 2010, in May 2011, in May, Juny and July 2012, which was expressed in the high values of the Selyaninov's index for these months. The driest year was 2012, when rainfall was lower than the monthly averages during the entire growing season, from April to September, except for July. Air temperatures from May to August, except in June, were higher than the long-term average in all years of the study.

Table 3

Daily air temperature, monthly precipitation and Selyaninov's coefficient values throughout the experiment

Year	Apr	May	Jun	Jul	Aug	Mean
	mean daily air temperature (°C)					
2010	7.0	13.1	14.3	19.3	18.6	14.5
2011	7.5	15.7	16.3	18.9	19.9	15.7
2012	6.4	14.4	17.6	19.2	18.4	15.2
Mean (1949-2012)	8.0	13.0	16.3	18.5	17.8	14.7
	Monthly precipitation (mm)					sum
2010	42.4	34.9	80.5	146.1	49.7	356.6
2011	17.7	111.5	31.3	77.9	58.0	296.4
2012	18.5	118.1	100.4	110.6	17.7	190.9
Mean (1949-2012)	27.2	43.9	54.4	72.9	55.8	254.2
	Selyaninov's coefficient					mean
2010	2.02	0.86	1.88	2.44	0.86	1.61
2011	0.79	2.29	0.64	1.33	0.94	1,20
2012	0.96	2.73	1.90	1.78	0.31	1.54
Mean (1949-2012)	1.22	1.01	1.15	1.26	0.95	1.12

The content of Mn, Fe, Zn and Cu in oat grain were determined by standard atomic absorption spectrometry (ASA), following mineralisation in a mixture of concentrated hydrochloric and nitric acids in a 1:3 ratio. ASA was carried out using a VARIAN AA240FS fast sequential atomic absorption spectrometer.

The results were analysed statistically by split-plot analysis of variance (ANOVA) according to a model consistent with the design of the experiment. The Tukey's range test with probability of $p = 0.05$ was used to estimate the significance of differences between means.

RESULTS AND DISCUSSION

Variable weather conditions led to changes in the oat grain yield in different years of the experiment. The highest yield was obtained in the 2012 growing season (on average 4.68 t ha^{-1}; Table 4). In May and June of that

Table 4

Yield of oat grain (t ha^{-1})

Year	Control	Form of fertiliser						Mean
		$(NH_4)_2SO_4$		K_2SO_4		Wigor S		
		(kg S ha^{-1})						
		20	40	20	40	20	40	
2010	3.79	4.03	4.17	3.89	4.01	4.29	4.19	4.05
2011	3.59	4.09	3.94	4.15	4.12	4.36	3.92	4.02
2012	4.47	4.82	4.55	4.58	4.75	4.85	4.76	4.68
Mean	3.95	4.31	4.24	4.21	4.29	4.50	4.29	4.25
		4.28		4.24		4.40		
$LSD_{0.05}$ – 0.18								

year, when grain formation and filling took place, the precipitation levels and Selyaninov's index were significantly higher than in the analogous periods of the other years and than the long-term average (Table 3). Oat belongs to cereals with high water requirements (Kordulasińska, Bulińska-Radomska 2014), and therefore this factor is likely to be a major yield determinant.

Although oat is a species with low sulphur requirements (Podleśna 2013), sulphur application, irrespective of the type of fertiliser applied, had a beneficial effect on grain yield in all years of the experiment. Depending on the fertiliser variant, the differences in grain yield between the fertilised and control treatments varied on average from 0.29 t·ha^{-1} (K_2SO_4) to 0.45 t ha^{-1} (Wigor S), or as a percentage difference by 7.3-11.4%. No statistically confirmed differences were noted between the grain yields of oat fertilised with different types of fertiliser. A beneficial effect of sulphur on the yield of cereals has been shown by numerous researchers (Griffiths et al. 1995, Eriksen, Mortensen 2002, Barczak 2010).

However, there are reports in the literature which do not confirm the positive effect of sulphur on cereal yields. For example, essentially no effect of this element on grain yield and its components was observed by Świderska--Ostapiak and Stankowski (2002) for cultivars of hulled and naked oat, or by Fotyma (2003) for winter and spring wheat. The lack of a positive effect of sulphur on yield was probably due to a sufficient supply of this nutrient to the plants in the experimental conditions. Many authors (Girma et al. 2005, Barczak 2010) emphasise that high efficiency of sulphur in increasing yield can be attained only in conditions of sulphur deficiency. According to a study by the Institute of Soil Science and Plant Cultivation (IUNG) in Poland, which monitors the chemistry of arable soils (Siebielec et al. 2012), as many as 203 profiles (94% of all samples) in Poland exhibited low (<15 mg kg^{-1}) content of available forms of sulphur in 2010. This suggests possible sulphur deficiencies over much of Poland's area. Furthermore, over the years 1995--2010, a marked tendency towards a growing shortage of this nutrient was observed.

For the fertilisers containing sulphur in an ionic form ($(NH)_2SO_4$ and K_2SO_4), generally no statistically confirmed differences were found in the effect on yield between the 20 and 40 kg ha^{-1} applications. As a three-year average, a significantly higher grain yield as compared to the other experimental treatments was obtained following an application of 20 kg S ha^{-1} in the form of Wigor S. This may indicate a slightly more beneficial effect of elemental sulphur on yield than that of the ionic form applied as ammonium or potassium sulphate. While the ionic form of sulphur is considered to be more easily assimilated by plants than elemental sulphur, which must undergo microbiological transformation to sulphate(VI) in soil, a process involving bacteria of the genus *Thiobacillus*, the ionic form, particularly in light soils, is more vulnerable to loss due to leaching. Our study was conducted on lessive soil characterised as loamy sand. In these conditions, the gradual release of sulphate(VI) ions accompanying progressing biological oxidation was more conducive to oat yield than a direct application of the ionic form.

The lowest mean content of iron, zinc and copper in the oat grain was noted in 2012 (Table 5), when the grain yield was highest (Table 4). This was most likely due to the dilution effect, which occurs when the increase in yield is greater than the increase in the content of the nutrient (Kaczor, Łaszcz-Zakorczmenna 2003).

It was only the content of manganese and copper in the oat grain that was significantly determined by the application of sulphur fertilisers. The highest average percentages of these elements were obtained in the case of ammonium sulphate(VI); the differences in comparison with the control were 8.7% and 30.6% for manganese and copper, respectively. The effect of

Table 5

The content of microelements in oat grain (mg kg^{-1})

Year	Control	Form of fertiliser						Mean
		$(NH_4)_2SO_4$		K_2SO_4		Wigor S		
		20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	
Content of manganese								
2010 2011 2012	31.2 27.6 37.9	33.0 29.6 39.9	35.1 30.6 41.7	32.0 26.3 38.3	33.0 28.8 38.6	33.3 26.6 40.5	33.5 26.4 40.3	33.0 28.0 39.6
Mean	32.2	34.2	35.8	32.2	33.4	33.5	33.4	33.5
		35.0		32.8		33.5		
$LSD_{0.05}$ – 1.20								
Content of iron								
2010 2011 2012	73.8 68.5 57.5	45.9 63.7 63.6	60.3 65.1 64.1	55.6 67.6 63.2	78.5 52.6 79.5	72.8 68.7 67.4	78.3 70.5 55.9	66.4 68.1 64.5
Mean	66.6	57.7	63.2	62.1	70.2	69.6	74.9	66.3
		60.5		66.2		72.3		
$LSD_{0.05}$ – n.s.								
Content of zinc								
2010 2011 2012	179.7 112.8 92.0	193.8 104.7 98.9	144.1 104.7 73.1	142.2 115.2 97.1	126.9 105.9 101.2	182.7 102.9 117.2	97.0 85.2 96.0	152.3 104.5 96.5
Mean	128.2	132.5	107.3	118.2	111.3	134.3	92.7	117.8
		119.9		114.8		113.5		
$LSD_{0.05}$ – n.s.								
Content of copper								
2010 2011 2012	4.30 5.41 3.90	5.73 6.76 4.54	6.27 7.49 5.12	3.67 7.11 4.53	5.07 6.10 4.68	4.97 5.24 3.83	6.00 6.54 5.14	5.14 6.37 4.53
Mean	4.54	5.66	6.29	5.10	5.28	4.68	5.89	5.35
		5.93		5.19		5.29		
$LSD_{0.05}$ – 0.702								

Wigor S was somewhat less beneficial, while potassium sulphate(VI) was the least effective. In general, all the tested fertilisers increased the content of the above nutrients with respect to the control.

An application of 40 kg S ha^{-1} in the form of ammonium sulphate(VI), as compared to the effect of 20 kg ha^{-1}, generally caused a significant increase in the content of manganese and copper in the oat grain. A similar correlation was noted for the copper content following an application of Wigor S.

Assessment of the supply of iron and manganese to crop plants involves the iron to manganese ratio. At iron deficiency, symptoms of manganese toxicity may develop, while manganese deficiency may occur under conditions of excessive iron supply in the soil. Therefore, an adequate balance must be maintained between these two elements. The supply of these nutrients is considered to be correct when the ratio between Fe and Mn in cereals ranges from 1.5:1 to 2.5:1 (Kabata-Pendias 2011). A lower ratio may result in symptoms of excessive manganese in the plants, accompanied by signs of iron deficiency, whereas a ratio greater than 2.5:1 may lead to a surplus of iron in the plant together with manganese deficiency (Błaziak 2007). The ratio of these microelements in the oat grain for two of the fertiliser variants in 2011 (20 kg ha^{-1} potassium sulphate and 40 kg ha^{-1} Wigor S) was not within this range (Table 6). Sulphur application, especially in the form of ammonium sulphate(VI), generally caused a reduction of this ratio.

Table 6

Quantitative Fe:Mn ratio in oat grain

Year	Control	Form of fertiliser						Mean
		$(NH_4)_2SO_4$		K_2SO_4		Wigor S		
		20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	
2010	2.37	1.39	1.72	1.74	2.38	2.19	2.34	2.01
2011	2.48	2.15	2.13	2.57	1.83	1.58	2.67	2.43
2012	1.52	1.59	1.54	1.65	2.06	1.66	1.39	1.63
Mean	2.12	1.71	1.79	1.99	2.09	2.14	2.13	2.02
		1.75		2.04		2.14		

The changes in this direction may be linked to the effect of the sulphur fertiliser on soil pH. This is suggested by the results of a Błaziak (2007) study, which demonstrates correlations between the application of calcium and magnesium to soil and the iron-manganese ratio in oat grain and straw.

The highest uptake by the oat grain was noted for zinc (on average 495 g ha^{-1}), followed by iron (276.9 g ha^{-1}), manganese (143.1 g ha^{-1}) and copper (22.5 g ha^{-1}) – Table 7. In different growing seasons, substantial variation was noted in the uptake of these nutrients in the grain, due to the significant differences in grain yield in successive years of the study (Table 2). The tested fertilisers affected the uptake of all microelements, but statistically confirmed differences between the fertiliser and control treatments were mainly found for manganese and copper. For all nutrients except iron, the fertiliser most conducive to their uptake appeared to be ammonium sulphate(VI), but the differences between the fertilisers were not confirmed statistically. The higher application dose (40 kg S ha^{-1}) of fertilisers containing ionic sulphur ($(NH)_2SO_4$ and K_2SO_4), in comparison with the dose of

Table 7

Micronutrient uptake by oat grain (g ha^{-1})

Year	Control	Form of fertiliser						Mean
		$(NH_4)_2SO_4$		K_2SO_4		Wigor S		
		20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	20 kg ha^{-1}	40 kg ha^{-1}	
Uptake of manganese								
2010	118.9	132.0	145.3	120.3	136.6	148.2	136.3	133.9
2011	98.8	123.4	119.0	110.7	116.9	112.0	107.4	112.6
2012	170.9	188.7	193.5	174.3	181.0	188.7	183.4	182.9
Mean	129.5	148.0	152.6	135.1	144.8	149.6	142.4	143.1
		150.3		140.0		146.0		
LSD $_{0.05}$ – 6.62								
Uptake of iron								
2010	281.2	183.6	249.6	209.1	325.0	324.0	318.7	270.2
2011	245.2	265.6	253.2	284.6	213.6	289.2	286.9	262.6
2012	259.3	300.8	297.4	287.6	372.9	314.1	254.3	298.1
Mean	261.9	250.0	266.7	260.4	303.8	309.1	286.6	276.9
		268.4		282.1		297.9		
LSD $_{0.05}$ – 56.70								
Uptake of zinc								
2010	684.7	775.2	596.6	534.7	525.4	813.0	394.8	618.8
2011	403.8	436.6	407.3	485.0	430.0	433.2	346.8	420.4
2012	414.9	467.8	339.2	441.8	474.6	546.2	436.8	445.9
Mean	501.1	493.6	516.3	487.2	476.7	597.5	392.8	495.0
		505.0		482.0		495.2		
LSD $_{0.05}$ – 121.51								
Uptake of copper								
2010	16.4	22.9	26.0	13.8	21.0	22.1	24.4	20.9
2011	19.4	28.2	29.1	29.9	24.8	22.1	26.6	25.7
2012	17.6	21.5	23.8	20.6	21.9	17.8	23.4	20.9
Mean	17.8	24.2	26.3	21.4	22.6	20.7	24.8	22.5
		25.3		22.0		22.8		
LSD $_{0.05}$ – 3.50								

20 kg S ha^{-1}, generally caused an increase in the uptake of micronutrients by the oat grain, which may have been due to the positive effect of sulphur on yield (Table 4), as well as the usually higher content of microelements following sulphur application at the higher dose (Table 5). In each year of the

study, the application of sulphur in the form of Wigor S (elemental sulphur) at a double dose caused an increased uptake of copper only.

CONCLUSION

Yield of oat grain following application of sulphur-containing fertilisers, irrespective of the type of fertiliser and application dose, was generally significantly higher than the grain yield of plants that were not fertilised with sulphur. Elemental sulphur applied in the fertiliser Wigor S had a more beneficial effect on yield than the ionic form applied as ammonium or potassium sulphate. Sulphur application exerted a significant effect on the content of only manganese and copper in the oat grain. In each year of the study, a slight increase in the content of these micronutrients was observed following application of sulphur as compared to their content in the grain of plants that were not fertilised with sulphur. Among the fertilisers applied, ammonium sulphate(VI) had the greatest effect on the content and uptake of all micronutrients tested, except for iron. There were no distinct differences noted between the effects of the application doses of 20 and 40 kg S ha^{-1} on either the oat grain yield or the content and uptake of the elements analysed. The positive effect of sulphur on yield and its generally positive effect on the content and uptake of the tested microelements in the oat grain indicated on the need to include this nutrient in cultivation for this species.

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