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ORIGINAL PAPER

INFLUENCE OF SULPHUR FERTILIZATION ON YIELDING AND CHEMICAL COMPOSITION OF GRAIN OF SPRING WHEAT (*TRITICUM AESTIVUM* L.) GROWN IN DIFFERENT HABITAT CONDITIONS*

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Abstract

The reduction of sulphur immission observed for many years and associated with significant reduction of its emissions from commercial power plants has reduced its amounts both in the air and soil to a level insufficient for arable crops. As a result, the negative balance for this component is deepening. Therefore, taking into account the role of sulphur in plant nutrition, the current state of knowledge limited mainly to winter oilsed rape and the progressing reduction of sulphur emissions into the atmosphere, studies have been performed to determine the effect of various sulphur fertilizers, both soil as well as soil and plant spray, on yield, yield components, plant physiological parameters and grain chemical composition depending on different sulphur contents in the soil (two locations). The experimental factors were: 2 locations (IUNG - PIB Puławy 51°24′59″ N - 21°58′09″ E, IOR - PIB Poznań 52°24′24″ N - 16°55′47″ E) and 6 variants of sulphur fertilization. Spring wheat fertilization with sulphur, regardless of the form of the fertilizer used, resulted in a significant increase in grain yield, TGW (1000 grains weight), SPAD (greening index) and N content in the grain. The best results of the applied sulphur fertilization on the yield, yield components and mineral composition of wheat grain were recorded in conditions of insufficient sulphur in soil. Among the fertilizers used, liquid Sulfone was characterized by clearly better yield-forming traits than any other fertilizer, regardless of a dose.

Keywords: sulphur fertilization, *Triticum aestivum* L., yield components, mineral compounds of grain, yield, SPAD index.

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INTRODUCTION

Sulphur is a very important nutrient for arable crops. This element affects the level of yield and quality of plant products, as well as increasing the tolerance of plants to biotic and abiotic stress (Györi 2005, Podleśna 2005, Sharma et al. 2009, Singh, Singh 2014). Sulphur also has a significant impact on the baking value of wheat grain (Tea et al. 2007). It was found that the proportion of sulphur in the chemical composition of plants is high, second only to carbon, hydrogen, oxygen and nitrogen (Scherer 2001). The role of sulphur in the proper growth and development of plants is versatile, but the most important function arises from the presence of this component in most proteins. It is part of the essential amino acids necessary for their synthesis, i.e. cystine, cysteine and methionine (Klikocka et al. 2016). An optimal supply of crops with sulphur is also of ecological importance, as its shortage leads to a reduction in the use of nitrogen from fertilizers, which may be a threat to the natural environment (Jackson 2000, Klikocka et al. 2017). Sources of sulphur as a fertilizer can be different – from elemental sulphur, through multi-component mineral fertilizers, specialized sulphur fertilizers to by-products from the power industry like gypsum from the flue gas desulphurization from boilers in power plants (Järvan et al. 2008).

Cereals take less sulphur than other crops. Studies on winter wheat fertilization concerned primarily the determination of optimal doses (Hoel 2011, Karamanos et al. 2013). For economic and natural reasons, optimization of fertilization with this element also requires the selection of a suitable form and date of fertilizer application (Gallejones et al. 2012, Podleśna et al. 2018).

Therefore, taking into account the role of sulphur in plant nutrition, the current state of knowledge limited mainly to winter oilseed rape and the progressing reduction of sulphur emissions into the atmosphere, studies have been performed to determine the effect of various sulphur fertilizers, both soil as well as soil and plant spray, on yield, yield components, plant physiological parameters and grain chemical composition depending on different sulphur contents in the soil (two locations).

MATERIAL AND METHODS

Plant material

A pot experiment with spring wheat was carried out in 2017. The experimental factors were: 2 locations (IUNG – PIB Puławy 51°24′59″ N – 21°58′09″ E, IOR – PIB Poznań 52°24′24″ N – 16°55′47″ E) and 6 variants of sulphur fertilization (CO – control, AG – Agrosupra, SA – Saletrosan, SU1 – Sulfone one dose, SU2 – Sulfone two doses, SU3 – three doses)

The research material consisted of spring wheat KWS Chamsin. The experiment was established in a complete randomization system at the number of replications $n = 4$. The experiments were carried out in pots of 28 cm in diameter and 20 dm^3 in capacity, filled with pseudopodzolic soil taken from the arable layer of experimental fields at the IOR Poznań and IUNG Puławy. The pots were protected from atmospheric precipitation, and the soil moisture was maintained at the optimal level (60% of the field's water capacity).

Wheat seeds (20 seeds per pot) were sown with the help of a matrix ensuring equal distance between seeds, to a depth of 3 cm. Sowing of wheat in the IUNG - PIB Puławy was performed on 3.04.2017, and in the IOR – PIB – on 5.04.2017. The harvest was carried out manually on 17.08.2017 in both locations.

Characteristics of fertilizers

The fertilizer application scheme is presented in Table 1. AgroSupra S is a sulphur-calcium fertilizer in the loose form. The calcium content is 23.5%,

Table 1

Characteristics of fertilization used in the experiments

<table>
<tr><th>Variant*</th><th>P</th><th>K</th><th>N</th><th>S</th></tr>
<tr><td rowspan="2">CO</td><td>1.2 g</td><td>1.2 g</td><td>3 g</td><td>--------</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>ammonium sulphate 1.5 g sowing + 1.5 g BBCH 31</td><td>--------</td></tr>
<tr><td rowspan="2">AG</td><td>1.2 g</td><td>1.2 g</td><td>3 g</td><td>1.2 g</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>ammonium sulphate 1.5 g sowing, + 1.5 g BBCH 31</td><td>before sowing, cover with soil</td></tr>
<tr><td rowspan="2">SA</td><td>1.2 g</td><td>1.2 g</td><td>1.6 g +2 g</td><td>1.2 g</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>Saletrosan + ammonium sulphate 0.8 g +1.0 g sowing, 0.8 +1.0 g BBCH 31</td><td>0.6 g sowing, 0.6 g BBCH 31</td></tr>
<tr><td rowspan="2">SU1</td><td>1.2 g</td><td>1.2 g</td><td>3 g</td><td>4.0 ml</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>ammonium sulphate 1.5 g sowing + 1.5 g BBCH 31</td><td>BBCH 12</td></tr>
<tr><td rowspan="2">SU2</td><td>1.2 g</td><td>1.2 g</td><td>3 g</td><td>4.0 ml + 2.0 ml</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>ammonium sulphate 1.5 g sowing +1.5 g BBCH 31</td><td>BBCH 12
BBCH 31</td></tr>
<tr><td rowspan="2">SU3</td><td>1.2 g</td><td>1.2 g</td><td>3 g</td><td>4.0 ml+ 2.0 ml + 2.0 ml</td></tr>
<tr><td>superphosphate 40%</td><td>potassium salt 60%</td><td>ammonium sulphate 1.5 g sowing +1.5 g BBCH 31</td><td>BBCH 12
BBCH 31
BBCH 52</td></tr>
</table>

Solution Sulfone 0.25% (0.25 kg 100 l^{-1} = 2.5 g 1 l^{-1}), * CO – control, AG – Agrosupra, SA – Saletrosan, SU1 – Sulfone one dose, SU2 – Sulfone two doses, SU3 – three doses while sulphur makes up 18.8%. Saletrosan 26 is a granulated fertilizer, which contains 26% nitrogen (N), including ammonium 19% and 7% in the form of nitrate. It also contains 13% sulphur (S). Sulfone is a white crystalline fertilizer which contains 20% phosphite P form nutri-phite, 15% sulphur from MSN (methyl sulphonyl methane), 15% potassium from potassium prosphite, 5% nitrogen, 0.5 chelated iron.

Soil conditions

The pH of the soil on which the experiments were conducted in both locations was slightly acidic. The phosphorus content in the soil ranged from high in Poznań to very high in Puławy; the content of potassium and magnesium varied from the average in Poznań to very high in Puławy; and that of sulphur was from high in Poznań to low in Puławy. The soil reaction and the content of nutrients (mg kg^{-1} soil) are shown in Table 2.

Table 2

Chemical properties of the soil

Location	pH_{KCl}	Humus (g kg^{-1})	P	K	Mg	S-SO_4
			(mg kg^{-1} soil)			
Poznań	6.0	19	74.8	162.7	37	17.2
Puławy	6.4	21	113.1	196.7	95	9.7

P – available phosphorus, K – available potassium Mg – available magnesium

Climatic conditions

Compared to a multiannual period, the growing season was clearly colder in Poznań and warmer in Puławy (Table 3). The average air temperature during the research period (April – August) was 15.8°C in Poznań, and 17.6°C in Puławy. In the months in which the research was conducted more favourable humidity conditions were recorded in Poznań (average air humidity 75.4%). In Puławy, the air humidity was at the level of 60.2% (Table 4).

Yield components

The following traits were determined in the experiment:

- number of plants after emergence per pot (BBCH 13),
- yield of grains per pot, number of plants before harvest, plant height, production propagation, ear length, number of grains per ear, 1000 grains weight (TGW), yield per ear and weight of roots from the pot.

Index of SPAD

The SPAD values (index of leaf greening) in phases BBCH 21- (SPAD I), BBCH 31 (SPAD II), BBCH 65 (SPAD III) were measured by the photo-optic method using a Minolta SPAD-502 analyzer (USA), on 10 randomly selected plants from each variant.

Table 3

Air decade temperatures (°C) during wheat growth in Poznań and Puławy in 2017

Location	Decade	Months				
		April	May	June	July	August
Poznań	1	11.1	8.8	17.2	17.2	22.1
	2	6.0	16.5	18.3	18.4	19.2
	3	6.8	17.2	18,9	20.1	-
	mean	7.9	14.1	18.1	18.5	20.6*
	multi-year**	9.6	14.5	18.0	20.0	20.3
Puławy	1	11.3	12.2	19.1	19.2	25.2
	2	5.7	16.0	19.4	19.9	22.0
	3	6,7	19.4	22.0	22.2	-
	mean	7.9	15.8	20.1	20.4	23.6*
	multi-year**	7.9	14.5	18.0	20.0	21.3

* mean value from 2 decades, ** mean from a multi-year period: Poznań (2003-2016), Puławy (1871-2017)

Table 4

Air decade humidity during the wheat growing period in Poznań and Puławy in 2017

Location	Decade	Months				
		April	May	June	July	August
Poznań	1	79	85	68	79	70
	2	77	69	74	76	78
	3	76	69	77	81	-
	mean	77	74	73	79	74*
Puławy	1	45	63	55	64	59
	2	48	57	66	67	65
	3	58	61	67	68	-
	mean	50	60	63	66	62*

* mean value from 2 decades

Chemical measurements

Nitrogen in wheat grain was determined in solutions after grain mineralization in sulphuric(VI) acid with H_2O_2 using the Kjeldahl method. Total content of potassium and magnesium after grain mineralization in a mixture of nitric(V) and chloric(VII) acids in a 1:1 ratio was determined using an atomic absorption spectrometer (Thermo Fisher Scientific ICE 3000 Series). Phosphorus was determined colorimetrically using ammonium molybdate at a wavelength of 470 nm (ISO 6491:1998). Total sulphur was determined on a CHNS elemental analyser (Costech International S.p.A Italy). Based on the sulphur content in the grain and taken up by the plant, a percent response was calculated, according to the following formula:

$$\% \text{ response} = 100 \cdot \frac{(\text{Y with S}) - (\text{Y without S})}{\text{Y without S}},$$

Y with S – grain yield g per pot, with sulphur,

Y without S – grain yield g per pot, without sulphur.

The soil pH_{KCl} was determined potentiometrically according to the ISO 10390:1997 norm. The amount of organic carbon was determined by the Westerhoff's colorimetric method. The content of humus was calculated by multiplying the content of carbon × 1.724 (Ostrowska et al. 1991). The content of available phosphorus (P) and potassium (K) was determined by the Egner-Riehm method (DL). Extraction with a buffered barium chloride solution pH = 8.1 (ISO 13536: 2002P) was used to determine the amount of available magnesium (Mg). The sulfate content was determined by the method according to ISO 11048:2002P norm.

Statistical analysis

The results were statistically analyzed using a 2-factor variance analysis in a completely randomization system. The confidence intervals were calculated using the HSD Tukey test at the significance level <0.05. Comparison of medium groups was based on the orthogonal contrast method created independently for two locations (Poznań and Puławy) due to the presence of a significant interaction between sulphur fertilization and the place of conducting the research. Significance was verified by the *F* test at the significance levels <0.05, 0.01 and 0.001. Multiple regression equations were determined by the ascending method, separately for the 2 experimental locations. Verification of the significance of multiple regression coefficient *R* was verified using *F* Fisher's test, and the significance of partial regression coefficients – *t*-Student's test. Statistica v.12 (StatSoft Inc. 2008) was used to perform the analyses.

RESULTS

As a result of sulphur fertilization, regardless of its dose and form, there was an increase in grain yield per pot, TGW, grain yield and index of SPAD values in phase BBCH 52 and nitrogen content in the wheat grain compared to the control object. The location did not significantly affect the Mg concentration in the grain of examined cereals and the greening index of SPAD. The interaction of both experimental factors (sulphur fertilization x location) significantly affected the grain yield, plant yield height, index of SPAD in phase BBCH 52 and concentration of nitrogen and sulphur in wheat grain (Table 5).

The most beneficial effects of sulphur fertilization were recorded in Puławy, which was probably influenced by the low content of this element in the soil in which the experiment was carried out. In comparison with

Table 5

Effects of sulphur fertilization (S), location (L) and their interaction on grain yield, yield components, SPAD and macroelements content in the grain

Traits	S F p	L F p	S x L F p	V(%#)
Yield and elements of the yield structure				
Grain yield (g pot^{-1})	5.81 ***	287.94***	5.11**	4.58
No. of plants per pot	2.25 ns	12.00***	2.25 ns	3.19
No. of ears per pot	2.81*	5.77**	1.14 ns	6.54
No of grains per ear	1.07 ns	164.28***	2.06 ns	7.61
TGW (g)	2.87*	6.63**	1.20 ns	5.69
Grain yield per ear (g)	4.00**	167.28***	4.44**	6.51
Ear lenght (cm)	1.08 ns	98.53***	2.10 ns	5.40
Plant height (cm)	2.24 ns	252.63***	4.37**	3.25
Roots weight per pot (g)	1.02 ns	153.80***	2.24 ns	13.5
Index of SPAD values				
SPAD I	1.06 ns	2.35 ns	2.26 ns	5.65
SPAD II	1.56 ns	1.02 ns	2.25 ns	5.24
SPAD III	5.20**	1.05 ns	11.21***	4.59
Content of elements in the grain				
N (g kg^{-1})	378.70***	716.73***	16.7***	2,20
P (g kg^{-1})	1.92 ns	883.25***	1.05 ns	2,83
K (g kg^{-1})	1.60 ns	22.76***	1.13 ns	5,47
Mg (g kg^{-1})	2.10 ns	1.07 ns	1.76 ns	4,38
S (g kg^{-1})	1.76 ns	231.0 ***	6.08**	10.1

Significance levels are *** $P < 0.001$, ** $P < 0.01$; * $P < 0.05$, ns – not significant;
Variability coefficient V% = $\sqrt{S^2_e}/x$, TGW – 1000 grains weight, SPAD – index of leaf greening

the wheat cultivated in Poznań (high sulphur content in soil), significantly higher grain yield per unit area (by 8.4 g, i.e. 23%), number of grains in the ear (by 13.3, or 34%), crop yield (about 0.47 g, i.e. 28%), ear length (by 1.3 cm, i.e. 16%), plant height (by 9.1 cm, i.e. 9.1%), weight of roots from the plant (by 395 g, i.e. 126%) and contents of nitrogen, phosphorus, potassium and sulphur (g·kg^{-1}) in wheat grain, respectively by 3.4 (15%), 1.89 (43%), 1.04 (21%), 0.52 (26%), were recorded (Table 6).

The sulphur fertilizers used in the experiment in a liquid and solid form positively influenced the yield and yield components (Table 7). Wheat fertilized with sulphur in comparison to that cultivated in control pots (without fertilization) was characterized by higher yield per unit area, TGW, yield per ear, greening index measured in phase BBCH 52 (III) and nitrogen content in grain. Significantly the largest grain yield was obtained from wheat fertil-

Table 6

Effects of locations (Poznań, Puławy) on grain yield, yield components and SPAD

Traits	Poznań (high content of $S\text{-}SO_4$ in the soil)	Puławy (low content of $S\text{-}SO_4$ in the soil)	$LSD_{0.05}$
Yield and elements of the yield structure			
Grain yield (g pot^{-1})	36.0	44.4	1,00
No. of plants per pot	19.0	20.0	ns
No. of ears per pot	21.8	20.8	ns
No of grains per ear	38.6	51.9	3.43
TGW (g)	43.2	41.4	1.42
Grain yield per ear (g)	1.67	2.14	0.071
Ear lenght (cm)	8.0	9.3	0.28
Plant height (cm)	56.3	65.4	1.15
Roots weight per plant (g)	0.312	0.707	0.068
Index of SPAD values			
SPAD I	34.9	34.0	ns
SPAD II	45.9	45.6	ns
SPAD III	47.9	48.2	ns
Content of elements in the grain			
N (g kg^{-1})	23.2	26.6	0.26
P (g kg^{-1})	4.36	6.25	0.138
K (g kg^{-1})	5.03	6.07	0.477
Mg (g kg^{-1})	1.28	1.28	ns
S (g kg^{-1})	1.98	2.50	0.197

ns – not significant, TGW –1000 grains weight, SPAD – index of leaf greening

ized with liquid fertilizer Sulfone in phase BBCH 12 and BBCH 31, on average by 3.7 g (i.e. 10%) per pot. The ear yield was the highest after applying Sulfone in the BBCH 12 phase, by 0.26 g (i.e., 15%) per ear. Significantly the largest TGW was achieved by the wheat fertilized with solid fertilizer Saletrosan 26, on average by 4 g (i.e. 10%) higher. The SPAD greening index measured in the BBCH 65 (III) phase was significantly the highest in the double-fertilized wheat (BBCH 12 and BBCH 31 phases), on average by 2 units (i.e. 4%). In the case of the grain's chemical composition, the most desirable nitrogen content in grain was recorded in wheat fertilized with Sulfone in the BBCH 12, BBCH 31 and BBCH 52 phases, better by 2.8 g kg^{-1} (i.e. 12%) than in the control.

It should be noted that while the conducted analysis of orthogonal contrasts (Table 8) did not show any significant differences between the type of sulphur used (solid and liquid) on yield of wheat grain cultivated in soil

Table 7

Effects of sulphur fertilization on grain yield, yield components and SPAD

Traits	CO	AG	SA	SU1	SU2	SU3	$LSD_{0.05}$
Yield and elements of the yield structure							
Grain yield (g pot^{-1})	38.5	38.8	39.7	40.3	42.2	41.5	2.61
No. of plants per pot	19.2	19.5	19.5	19.9	19.6	19.2	ns
No. of ears per pot	22.1	21.0	20.8	20.1	22.2	21.4	ns
No of grains per ear	44.4	44.6	44.0	46.4	46.4	45.7	ns
TGW (g)	39.8	41.9	43.8	43.4	41.7	42.9	3.27
Grain yield per ear (g)	1.75	1.86	1.92	2.01	1.93	1.96	0.194
Ear lenght (cm)	8.6	8.6	8.7	8.9	8.7	8.4	ns
Plant height (cm)	59.5	61.7	62.3	61.2	60.0	60.5	ns
Roots weight per plant (g)	0.527	0.479	0.515	0.555	0.537	0.440	ns
Index of SPAD values							
SPAD I	34.4	35.1	34.1	33.9	34.1	35.3	ns
SPAD II	45.5	45.0	46.8	45.1	45.2	46.9	ns
SPAD III	47.2	48.6	48.3	48.5	49.2	46.0	2.13
Content of elements in the grain							
N (g kg^{-1})	23.1	25.1	25.0	25.0	25.1	25.9	0.64
P (g kg^{-1})	5.20	5.27	5.49	5.28	5.21	5.37	ns
K (g kg^{-1})	5.84	5.76	5.51	5.37	5.31	5.50	ns
Mg (g kg^{-1})	1.25	1.29	1.29	1.24	12.28	1.35	ns
S (g kg^{-1})	2.10	2.20	2.30	2.20	2.45	2.30	ns

CO – control, AG – Agrosupra, SA – Saletrosan, SU1 – Sulfone one dose, SU2 – two doses, SU3 – three doses, TGW–1000 grains weight, SPAD – index of leaf greening, ns – not significant

with high sulphur content (Poznań), such a significant difference was found for wheat cultivated in soil characterized by a low concentration of this element (Puławy). Wheat cultivated in Puławy yielded significantly better, plants were higher, and were characterized bya significantly higher value of the index of SPAD III and nitrogen content in the analyzed grain (Table 9, Figure 1). The highest yield of wheat (grain yield per ear) was recorded in pots fertilized with Sulfone in phase BBCH 12, while the highest plants were in the pots fertilized with Saletrosan 26. Sulfone applied in phases BBCH 12, BBCH 31 increased the greening of leaves (index of SPAD III). In turn, when given in BBCH 12, BBCH 31 and BBCH 52 phases, it contributed to the increased concentration of nitrogen in the grain. Significantly, the largest grain yield per pot was obtained from wheat cultivated in Puławy and fertilized with Sulfone in the BBCH 12 and BBCH 31 phases (Figure 1).

On the basis of the results, the regression equation was determined (Table 10, Figures 2, 3) between wheat grain yield and the number of grains

Table 8

The orthogonal contrasts for grain yield differences affected by sulphur fertilization variants in 2 location (Poznań, Puławy)

Location	Comparison	Difference of mean values for groups	Significance
Poznań (high content of S-SO_4 in the soil)	$C1 =(x_{AG} + x_{SA} + x_{SU1} + x_{su2} + x_{SU3})/5 - x_{CO}$	-0.4	ns
	$C2 = (x_{AG} + x_{SA})/2 - x_{CO}$	-1.1	ns
	$C3 = (x_{SU1} + x_{su2} + x_{SU3})/3 - x_{CO}$	+0.0	ns
	$C4 = (x_{SU1} + x_{su2} + x_{SU3})/3 - (x_{AG} + x_{SA})/2$	+1.1	ns
Puławy (low content of S-SO_4 in the soil)	$C1 =(x_{AG} + x_{SA} + x_{SU1} + x_{su2} + x_{SU3})/5 - x_{CO}$	+4,3	***
	$C2 = =(x_{AG} + x_{SA})/2 - x_{CO}$	+2.5	**
	$C3 = (x_{SU1} + x_{su2} + x_{SU3})/3 - x_{CO}$	+5.8	***
	$C4 = (x_{SU1} + x_{su2} + x_{SU3})/3 - (x_{AG} + x_{SA})/2$	+3.0	**

Significance levels are: *** $P < 0.001$, ** $P < 0.01$; * $P < 0.05$, ns – not significant

Table 9

Significant interaction of experimental factors (fertilization and location) on grain yield per ear, plant height, SPAD III, N grain concentration

Traits	Location	CO*	AG	SA	SU1	SU2	SU3
Grain yield per ear (g)	Poznań	1.68	1.66	1.63	1.73	1.58	1.70
	Puławy	1.81	2.07	2.22	2.28	2.27	2.20
	$LSD_{0.05}$	0.245					
Plant height (cm)	Poznań	57.0	58.2	56.2	56.3	54.0	56.6
	Puławy	62.1	65.3	68.4	66.2	66.1	64.4
	$LSD_{0.05}$	3.78					
SPAD III	Poznań	49.9	49.6	48.1	48.1	48.7	43.2
	Puławy	45.6	47.7	48.5	48.9	49.8	48.8
	$LSD_{0.05}$	2.71					
Grain N g (kg^{-1})	Poznań	22.7	23.4	23.3	23.0	23.1	24.1
	Puławy	23.5	26.7	26.9	27.0	27.2	27.8
	$LSD_{0.05}$	0.89					

* CO – control, AG – Agrosupra, SA – Saletrosan, SU1 – Sulfone one dose, SU2 – two doses, SU3 – three doses, SPAD – index of leaf greening, ns – not significant

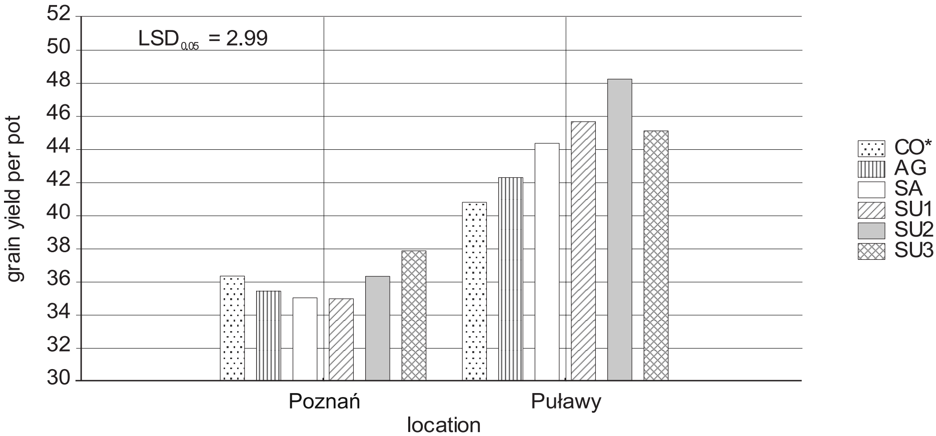

Fig. 1. The effect of sulphur fertilization and location on grain yield per pot (g)
CO – control, AG – Agrosupra, SA – Saletrosan, SU1 – Sulfone one dose, SU2 – two doses, SU3 – three doses

Table 10

Regression equations between grain yield (Y) and yield components, x_1 – number of grains per ear, x_2 – (TWG) and yield (Y) and x_3 (SPAD III) in two location (Poznań and Puławy), n = 24

Location	Regression equation	R^2
Poznań (high content of S-SO_4 in the soil)	$Y= 20.66^{*} + 0.168x_1^{*}+ 0.376\ x_2^{*}$	0.420^{*}
Puławy (low content of S-SO_4 in the soil)	$Y= -7.93^{*}+ 0.615x_1^{***}+ 0.516x_2^{**}$	0.703^{**}
	$Y= -2.66^{*} +0.975x_3^{**}$	0.486^{*}

Significance levels are: *** $P < 0.001$, ** $P < 0.01$; * $P < 0.05$

per ear, TWG and index of SPAD III. It was found that in both locations, there was a significant relationship between the wheat yield and analyzed yield components. An increase in the number of grains in the ear by one unit resulted in an increase in wheat yield by 0.17 g in Poznań and by 0.61 g in Puławy. The TWG higher by one unit increased the yield by 0.38 g in Poznań and by 0.52 in Puławy. Increasing the greening index (SPAD III) by one unit resulted in an increase in the wheat yield cultivated in Puławy by 0.97 g.

DISCUSSION

Number of ears per area unit, number of kernels in the ear and TGW – these components are in direct connection with productivity of wheat (Knezevic et al. 2007). According to our own research, the number of grains in the ear ($p < 0.001$), the number of ears per surface unit and TGW

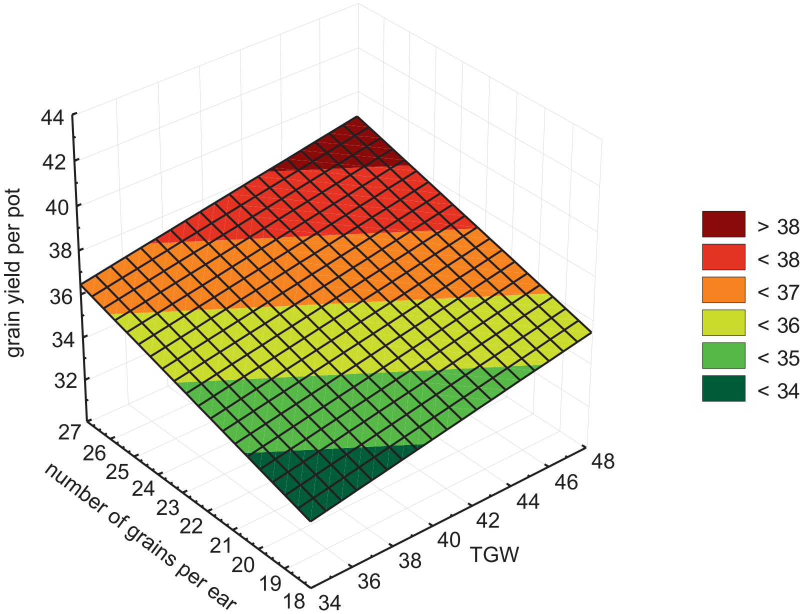

Fig. 2. Grain yield per pot (y) as affected by number of grains per ear (x_1) and TGW (x_2) in Poznań. Multiple regression equation $y = 20.66 + 0.168x_1 + 0.376\ x_2$

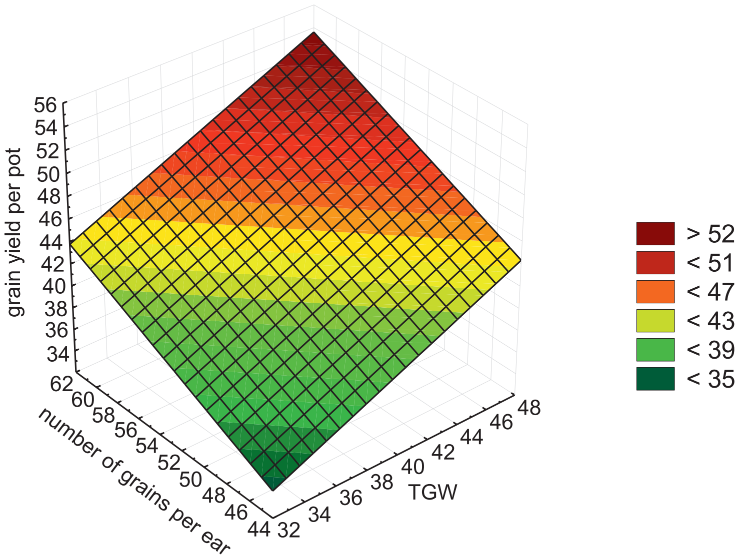

Fig. 3. Grain yield per pot (y) as affected by number of grains per ear (x_1) and TGW (x_2) in Puławy. Multiple regression equation $y = -\ 7.93 + 0.615x_1 + 0.516\ x_2$

($p < 0.01$) were shaped the most by the habitat conditions of the experiment (location). Sulphur fertilization significantly affected the studied characteristics at the level of $p < 0.05$ (Table 5). The increase in the number of ears per unit area in winter wheat fertilized with sulphur was observed by Järvan et al. (2012). They also confirmed that the sulphur used, while increasing the number of ears per surface unit on average by 14.0%, the number of grains in the ear by an average of 18.6%, and the wheat yield by 1.16 t ha^{-1} on average, i.e. by 23.0%, decreased the TGW at the same time. In our research, the sulphur used increased both the yield of wheat grain and TGW. Better yield and greater TGW in wheat fertilized with nitrogen in combination with sulphur was also reported by Hayat et al. (2015).

The content of chlorophyll in leaves is an important parameter for farmers and plant physiologists; it is an indicator of aging of leaves and the status of nitrogen in plants (Nauš et al. 2010). In the conducted studies, a significant increase in the greening index measured in phase BBCH 52 was found (Table 5). The relationship between the chlorophyll content in leaves and nitrogen and sulphur fertilization was confirmed by Skudra, Ruza (2017), who recorded an increase in the chlorophyll concentration in leaves of wheat fertilized with sulphur.

Previous studies have shown that sulphur fertilization significantly changes the chemical composition of crops. The availability of sulphur affects the effective use of nitrogen by plants, which affects the composition and quality of plants (Krauze, Bowszys 2000). Sulphur is an important component of nitrogen metabolism enzymes; its deficiency reduces absorption of nitrogen affecting the protein content and proportions of glutenin and gliadin within the protein, which influences the quality of flour (Zörb 2012, Sun 2016). Increasing the use of sulphur fertilization on soils with sulphur limitation could increase the content and improve protein quality in wheat flour (Tao et al. 2018). In our studies, nitrogen concentration was significantly modified by the soil content of sulphur available to plants (Tables 5, 6). A similar relationship concerned other analyzed features. According to Wielebski (2008), the effect of sulphur on the yield of seeds is important only in worse soil conditions and in the less sulphur-supplied plants. An analysis of the current results confirms that in conditions of insufficient sulphur in soil (Puławy), the sulphur supply of plants significantly affected the yield increase, analyzed yield components and levels of P, Mg and S in wheat grain, compared to wheat cultivation on soil with a high content of this element (Poznań) – Tables 5, 6.

Data published in the literature on the relationship between the form of fertilizer used and the size and quality of the crop (Jalloh et al. 2009, Gagnon et al. 2012) indicate a significant correlation between these features. According to some researchers, there are no significant differences in the efficiency between liquid and solid fertilizers. In turn, Watson et al. (1992) suggest better yields of liquid products, as well as their superior environmental performance due to better plant availability and more efficient uptake. The greater effect of using liquid fertilizers is confirmed by Lombi et al. (2002). In this study, the yield stimulating effects on objects where liquid fertilizers were used (Sulfone) were significantly higher compared to the equivalent doses of solid fertilizers. Sulfone (liquid fertilizer) contributed to significantly higher grain yield per unit area, grain yield per ear, SPAD III greening index and nitrogen concentration in the grain (Table 7, Figure 1). An exception was TGW, which was clearly higher in wheat fertilized with Saletrosan (solid fertilizer). The nitrogen uptake with grain yield of wheat fertilized with Sulfone was higher, which may indicate better absorption of this nutrient from liquid fertilizers. These results are comparable with those of Sztuder, kaus (2007) on the assessment of various fertilizer application methods in the cultivation of winter wheat. Better effects of cereal fertilizers in the liquid form compared to the solid form are also confirmed by Rimar et al. (1996). Irrespective of a fertilizer form, more nitrogen in wheat grain fertilized with sulphur was also found by Khan et al. (2015).

For the proper wheat growth and yield, it is necessary to provide it with nutrients, including macroelements. The high phosphorus content in wheat grain has a positive effect on the growth and development of these plants, especially in the first growing season. Magnesium deficiency lowers the photosynthetic efficiency of plants, decreases yields and deteriorates their quality, including it lowers the protein content in cereal grain. In turn, the optimal potassium content increases the utilization of nitrogen from fertilizers in plants, as well as the efficiency of converting this element into usable yield. There was no significant effect of sulphur fertilization on the content of phosphorus, potassium, magnesium and sulphur in the grain, compared to the control. The mineral composition did not differentiate between the forms of applied fertilizers (Tables 5, 7). These results were not confirmed by Gondek, Gondek (2010), who found that the sulphur content in both vegetative (straw) and generative (grain) parts of wheat fertilized with this mineral was significantly higher than the content of this component in wheat biomass in the control object. The same conclusions with the authors quoted above were presented by Kozera et al. (2017), who investigated the reaction of spring barley on fertilization with NPK and S. The grain of spring barley fertilized with sulphur was characterized by much higher amounts of nitrogen, phosphorus and potassium (Klikocka et al. 2014).

In our research, significant differences between the forms of fertilizers used (liquid and solid) in relation to grain yield were recorded only on the soil with sulphur deficiency (Table 8). Clearly better results were obtained in wheat fertilized with the liquid fertilizer (Sulfone). In the conditions of poor soil sulphur supply it was only the wheat height that was significantly higher in pots fertilized with the solid fertilizer (Saletrosan) – Table 9.

The wheat yield increased with an increase in the number of grains per ear and TGW by one unit in both analyzed locations (Table 10, Figures 2, 3). Similar relationships were reported by Harasim et al. (2016).

CONCLUSIONS

1. Spring wheat fertilization with sulphur, regardless of the form of the fertilizer used, resulted in a significant increase in grain yield, number of ears from the surface unit, TGW, SPAD greening index and N content in the grain, in comparison with the NPK fertilization.

2. The best results of the applied sulphur fertilization on the yield, yield components and mineral composition of wheat grain were recorded in conditions of insufficient sulphur in soil (Puławy).

3. Among the fertilizers used, liquid Sulfone was characterized by clearly better yield-forming traits than any other fertilizer, regardless of a dose.

4. Increasing the number of grains in the ear and TGW resulted in a larger increase in grain yield in conditions of higher rather than lower sulfur content in the soil.

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