Journal of Elementology ISSN 1644-2296

Jankowski K.J., Kijewski Ł., Groth D., Skwierawska M., Budzyński W.S. 2015. *The effect of sulfur fertilization on macronutrient concentrations in the post-harvest biomass of rapeseed (Brassica napus* L. *ssp. oleifera* Metzg*)*. J. Elem., 20(3): 585-597. DOI: 10.5601/jelem.2014.19.4.842

THE EFFECT OF SULFUR FERTILIZATION ON MACRONUTRIENT CONCENTRATIONS IN THE POST-HARVEST BIOMASS OF RAPESEED (*BRASSICA NAPUS* L. SSP. *OLEIFERA* METZG)*

Krzysztof J. Jankowski[1], Łukasz Kijewski[1], Dariusz Groth[1], Małgorzata Skwierawska[2], Wojciech S. Budzyński[1]

[1]Chair of Agrotechnology, Agricultural Production Management and Agribusiness
[2]Chair of Agricultural Chemistry and Environmental Protection
University of Warmia and Mazury in Olsztyn

Abstract

Brassica oilseed crops have very high sulfur requirements. The progressive decrease in the sulfur content of soil, the growing share of cruciferous vegetables in agricultural ecosystems and a significant drop in annual wet and dry deposition of sulfur have prompted a growing body of research into sulfur as a valuable fertilizer ingredient. The aim of this study was to determine the effect of sulfur fertilizers applied to soil on nitrogen, phosphorus, potassium, calcium, magnesium and sulfur concentrations in the root residues, straw and oil cake of winter and spring rapeseed. The experimental material was collected from a field experiment conducted in 2005-2008 at the Agricultural Experiment Station in Bałcyny (Poland).

The highest concentrations of nitrogen, phosphorus, magnesium and sulfur were noted in the oil cake of both winter and spring rapeseed. Potassium levels were highest in the root residues of winter and spring rapeseed. Winter rapeseed accumulated the highest amounts of calcium in roots, and spring rapeseed – in straw.

Sulfur fertilizers applied to soil decreased nitrogen concentrations and increased calcium and sulfur levels in the roots of both spring and winter rapeseed, whereas phosphorus concentrations increased only in the roots of winter rapeseed. Sulfur fertilization led to a drop in the potassium content of winter rapeseed roots (by 0.7 g kg^{-1} DM) and an increase in potassium levels in spring rapeseed roots (by 1.2 g kg^{-1} DM). The application of sulfur fertilizers significantly increased potassium and sulfur concentrations in the straw of both spring and winter rapeseed (by 1.3-1.7 and 0.5-0.6 g kg^{-1} DM, respectively). The application of sulfur fertilizers at optimal

dr hab. Krzysztof Jankowski, Chair of Agrotechnology, Agricultural Production Management and Agribusiness, University of Warmia and Mazury in Olsztyn, Oczapowskiego 8/117, 10-719 Olsztyn, Poland, e-mail: krzysztof.jankowski@uwm.edu.pl
* Supported by the Polish Ministry of Science and Higher Education, Project No. N310 031 32/167.

doses for winter rapeseed significantly increased the calcium content of straw (by 1.3 g kg^{-1} DM), but did not lead to differences in nitrogen levels. Sulfur fertilization significantly reduced nitrogen (by 0.7 g kg^{-1} DM) and calcium (by 0.6 g kg^{-1} DM) concentrations of spring rapeseed straw. The content of all the analyzed macronutrients increased significantly in spring rapeseed oil cake in response to sulfur fertilization. Sulfur also increased the concentrations of the evaluated macronutrients, excluding nitrogen and phosphorus, in winter rapeseed oil cake.

Keywords: winter rapeseed, spring rapeseed, root residues, straw, oil cake.

INTRODUCTION

Oilseed plants of the family *Brassicaceae* are good forecrops on account of their high fertilizing value and high biological value of their post-harvest residues. Growing of wheat after winter oilseed rape resulted in an increase of grain yield by *ca* 0.76-0.98 Mg ha^{-1} (Sieling et al. 2005, Wesołowski et al. 2007, Bednarek et al. 2009) and some improvement of quality parameters of flour and bread (Jankowski et al. 2014*b*).

The chemical composition of forecrop residues is an important indicator of their fertilizing value (Batalin 1962, Malicki 1997). It determines the rate of residue decomposition by soil-dwelling microorganisms, thus affecting the mineralization and humification of soil organic matter and as well as the composition and fertilizing value of humic compounds (Malicki 1997). In conventional farming systems, crop residues usually induce changes in the 0-15 cm soil layer (Malhi, Lemke 2007).

In an early study of traditional winter rapeseed cultivars characterized by a high content of erucic acid and glucosinolates (GLS), Batalin (1962) observed that root residues contained high levels of nitrogen and potassium (16 and 14 g kg^{-1} DM), moderate levels of calcium (9 g kg^{-1} DM) and low levels of phosphorus (4 g kg^{-1} DM). Kotecki et al. (2001), while Jasińska et al. (2002) observed insignificant differences in the chemical composition of root residues (roots and stubble) between double-low varieties of winter rapeseed (with a reduced content of erucic acid and GLS) and traditional varieties. The roots of double-low varieties accumulate mostly potassium and calcium, and are less nitrogen abundant. The highest concentrations of potassium (24 g kg^{-1} DM) are found in roots of double-low varieties of spring rapeseed. Nitrogen, phosphorus and calcium levels are nearly two-fold lower, magnesium concentrations are 10-fold lower, and sulfur levels are 20-fold lower than potassium concentrations (Szczebiot, Ojczyk 2002).

In a study by Spiak et al. (2007), the average nitrogen content of winter rapeseed straw was determined in the range of 4.0 to 4.7 kg^{-1} DM. Excessive potassium and calcium uptake by plants leads to several-fold higher concentrations of those elements in vegetative organs than in seeds. In the cited study, potassium concentrations in straw were estimated at 7.4-11.2 g kg^{-1} DM, and they were two-fold higher than in seeds. Calcium levels reached 20 g kg^{-1}

DM in the vegetative organs of winter rapeseed plants, but did not exceed 4 g kg^{-1} DM in the seeds. Winter rapeseed straw had a relatively low content of phosphorus (0.7-0.8 g kg^{-1} DM) and magnesium (0.7-1.0 g kg^{-1} DM) (Spiak et al. 2007). In the work of Wyszkowski and Wyszkowska (2004), the aerial parts of spring rapeseed plants accumulated high concentrations of nitrogen and potassium (15 and 19 g kg^{-1} DM), moderate levels of calcium (9 g kg^{-1} DM) and low levels of phosphorus and magnesium (2 and 3 g kg^{-1} DM).

The oil cake and meal of winter rapeseed are most nitrogen abundant (48 g kg^{-1} DM). The concentrations of potassium, phosphorus, calcium and sulfur are 4.4-, 5.3-, 7.8- and 9.2-fold lower, respectively, than nitrogen levels (Kalembasa, Adamiak 2010). Nitrogen concentrations are generally higher in the oil cake and meal of spring oilseed plants than of winter rapeseed (Malarz 2008, Jankowski et. al 2015). The oil-free seed residues of spring rapeseed contain mostly phosphorus (approximately 10 g kg^{-1} DM) but their calcium and magnesium content is nearly two-fold lower than their phosphorus content (Bell et al. 1999).

In comparison with other crops, oilseed crops of the family *Brassicaceae* have high sulfur requirements, mainly attributable to their ability to synthesize glucosinolates (GLS), biologically active compounds. All GLS contain sulfur and glucose, but they differ in the structure of aglycone, which determines the properties of those compounds (Zukalová, Vašák 2002). In *Brassicaceae* plants, sulfur fertilization, even at optimal dosage, increases GLS concentrations in roots, straw and seeds (oil cake) (Jankowski et al. 2015). Higher GLS concentrations in plant tissues strongly influence the plant-soil -pest/pathogen system (Troczyńska 2005). Sulfur fertilization can modify the pH and microbial activity of soil, which affects the biomass quality of sulfur -loving plants. The above can increase the concentrations of selected elements in plant tissue, in particular heavy metals (Salt et al. 1995, Chlopecka et al. 1996, Blaylock et al. 1997, Chaignon et al. 2002, Cui et al. 2004). In a study by Jankowski et al. (2014*a*), sulfur fertilization increased manganese levels and decreased copper concentrations in the root residues of spring and winter rapeseed, whereas zinc levels increased only in the roots of winter rapeseed. When applied to soil, sulfur increased the zinc and manganese content of winter rapeseed straw, but did not differentiate their concentrations in spring rapeseed straw. Sulfur fertilization led to a significant increase in zinc and manganese levels in winter rapeseed oil cake and a significant decrease in the manganese content of spring rapeseed oil cake (Jankowski et al. 2014*a*). Sulfur disturbs the rhizosphere balance, and it can also strongly affect macronutrient uptake by rapeseed plants (Podleśna 2004). A pot experiment conducted by Kaczor and Brodowska (2003) revealed that sulfur fertilization modifies the anion composition of winter rapeseed plants. This is an important consideration in agricultural production because mineral concentrations in plant tissues influence the rate of plant growth and development as well as the resistance to disease, freezing and other stressors during the growing season. By modifying the mineral content of sulfur-loving plants, sulfur fertilization can significantly influence the fertilizing value of their post-harvest residues (roots, straw) and the quality of plant material for oil extraction, measured by the chemical composition of seeds (Jankowski 2014*ac*).

The objective of this study was to determine the macronutrient (N, P, K, Ca, Mg and S) content of the root residues, straw and oil cake of winter and spring rapeseed fertilized with sulfur applied to soil.

MATERIAL AND METHODS

Field experiment

The field experiment was conducted in 2005-2008 at the Agricultural Experiment Station in Bałcyny (N = 53°35′49″; E = 19°51′20.3″). The experimental variables were:

first-order variable – a botanical form of rapeseed: winter rapeseed, spring rapeseed;

second-order variable – a dose of sulfur fertilizer applied to soil: (-S) control – no sulfur fertilization, (+S) winter rapeseed – 60 kg ha^{-1}; spring rapeseed – 40 kg ha^{-1}.

The experiment had a completely randomized design with three replications. The plot size was 18 m^2. Each year, the experiment was established on silty grey-brown podsolic soil developed from light loam (agricultural suitability class II on the Polish soil classification scale). The soil had a slightly acidic pH ranging from 5.75 to 6.39 in 1 M KCl. Soil nutrient levels were as follows: 1.47-1.75% C_{org}, 85-143 mg kg^{-1} P, 104-133 mg kg^{-1} K, 51-103 mg kg^{-1} Mg, 10-25 mg kg^{-1} SO_4^{2-} – 2.8-4.4 mg kg^{-1} Cu, 11-23 mg kg^{-1} Zn and 180--235 mg kg^{-1} Mn. The C_{org} content of soil was determined with the use of the modified Kurmies method. pH was measured with an electronic pH meter with temperature compensation (20°C) in deionized water and 1 M KCl in a 5:1 ratio. Plant-available phosphorus and potassium were extracted with calcium lactate solution (the Egner-Riehm method). Phosphorus concentrations were determined by the vanadium molybdate yellow colorimetric method, and potassium levels – by atomic emission spectrometry (AES). Magnesium was extracted with 0.01 M $CaCl_2$, and magnesium concentrations were determined by atomic absorption spectrophotometry (AAS). Soil micronutrients (copper, zinc, manganese) were extracted with 1 M HCl and their concentrations were determined by AAS. Sulfate sulfur was determined by extracting a soil sample with acetate buffer in accordance with the method proposed by Bardsley and Lancaster.

The performed farming operations are presented in Table 1. Phosphorus was applied to soil as triple superphosphate, potassium – as 60% potash salt, sulfur – as ammonium sulfate, nitrogen – as ammonium nitrate (-S) or as

Table 1

Oilseed crop production process

Farming operation		Month of operation and agricultural inputs	
		winter rapeseed	spring rapeseed
Skimming (5-8 cm)		July	July
Pre-sowing ploughing (15-18 cm)		August	–
Fall ploughing (18-22 cm)		–	October
Sowing		cv. Californium (90[a]) August	cv. Hunter (140[a]) April
Mineral fertilization	pre-sowing N/P/K[b]	30/24/166, August	70/17/100, April
	top-dressing N[b]	120 + 80, March + April	30, May
Chemical crop protection	herbicides[c]	1456.5 + 52.0, August + September	1248, April
	insecticides[c]	330-351[d], April, May	86-416[d], April, May, June
	fungicides[c]	200, May	–
Seed and straw harvest		July	August

[a] germinating seeds per 1 m^2; [b] kg ha^{-1}; [c] g ha^{-1} active ingredient (a.i.); [d] variations resulting from differences in pest intensity in each year of the study

ammonium sulfate and ammonium nitrate (+S). In winter rapeseed treatments, sulfur was applied with the first spring rate of nitrogen fertilizer. In spring rapeseed treatments, sulfur was applied with the pre-sowing rate of nitrogen.

Rapeseed was harvested at two stages upon the achievement of processing maturity. Winter and spring rapeseed plants were cut at a height of 8 cm. The biomass yield per 1 ha of spring and winter rapeseed was presented by Jankowski et al. (2014*a*).

Determination of macronutrient concentrations in biomass

Macronutrient concentrations (N, P, K, Ca, Mg, S) were determined in the root residues (roots and stubble), straw and oil cake of winter and spring rapeseed on a dry matter basis. Samples for chemical analyses (roots with stubble, straw and seeds) were collected upon harvest. Roots with stubble and soil were sampled with a steel cylinder (diameter of 22.6 cm, area of 400 cm^2) to a depth of 30 cm. The samples were rinsed with water in a sieve with 1 mm mesh size. Seed samples were cold pressed in a laboratory press with the estimated output of 50 kg h^{-1}. The oil content of cake ranged from 127 g kg^{-1} DM (winter rapeseed) to 129 g kg^{-1} DM (spring rapeseed). Samples of dried roots with stubble, straw and oil cake were ground in a laboratory mill. The samples were wet mineralized in H_2SO_4, and N_{org} concentrations were determined by the Kjeldahl method, P concentrations – by the vanadium-molybdenum method, K and Ca concentrations – by the flame atomic emission spectrometric method (ESA), and Mg concentrations – by AAS.

Total sulfur was determined turbidimetrically in plant material that had been incinerated with nitric acid and magnesium nitrate to sulfate form. The results were checked against certified reference materials (CTA VTL-2) with the error of: P – 4.5%, K – 2%, Ca – 2.8%, Mg – 1.5%.

Statistical analysis

The results of chemical analyses were processed by analysis of variance (Anova) in accordance with the experimental method. The average values of the tested parameters from each treatment were compared by the Duncan's test ($P \leq 0.05$). Data were processed in the Statistica 10.1 PL application.

RESULTS AND DISCUSSION

Root residues

Kotecki et al. (2001) and Jasińska et al. (2002) demonstrated that the root residues (roots and stubble) of winter rapeseed accumulate mainly potassium (8.0-8.3 g kg^{-1} DM), calcium (7.7-8.6 g kg^{-1} DM) and nitrogen (6.6-7.1 g kg^{-1} DM). Phosphorus and magnesium concentrations in the roots and stubble of winter rapeseed were five- to six-fold lower than nitrogen, potassium and calcium levels. The roots of spring rapeseed accumulated high levels of potassium (24.4 g K kg^{-1} DM) and moderate levels of nitrogen, phosphorus and calcium (8.7-9.9 g kg^{-1} DM). The magnesium and sulfur content of spring rapeseed roots was five-fold and seven-fold lower, respectively, than the average nitrogen, phosphorus and calcium concentrations (Szczebiot, Ojczyk 2002).

The roots of both winter and spring rapeseed accumulated significant amounts of potassium (16-19 g kg^{-1} DM) – Table 2. The concentrations of the remaining macronutrients in rapeseed roots were from two-fold (N, Ca) to 11-fold (P, Mg, S) lower than potassium levels on average. In general, higher quantities of macronutrients were accumulated by the roots of winter rapeseed than spring rapeseed. Statistically significant differences between the botanical forms of rapeseed were noted in magnesium, calcium and sulfur levels. Magnesium and sulfur concentrations were from 1.8- to 1.9-fold higher, and calcium concentrations were 2.6-fold higher in the root residues of winter rapeseed, compared with spring rapeseed (Table 2).

Sulfur fertilization significantly differentiated the chemical composition of the root residues of winter and spring rapeseed (Figure 1). Sulfur fertilizers applied to soil significantly decreased nitrogen concentrations (0.4-0.6 g kg^{-1} DM), but increased calcium (0.6-1.3 g kg^{-1} DM) and sulfur (0.5-0.7 g kg^{-1} DM) levels in the roots of both winter and spring rapeseed. Sulfur fertilization had a varied impact on phosphorus and potassium concentrations in the roots of winter and spring rapeseed. Winter rapeseed roots accumulated si-

Table 2

Macronutrient concentrations in the post-harvest biomass of winter and spring rapeseed (mean values of experimental factors) in 2005-2008

Experimental factor	Content (g kg^{-1} DM)					
	N	P	K	Ca	Mg	S
Root residues (roots + stubble)						
Winter rapeseed	9.8a*	1.7a	19.4a	11.6a	1.7a	2.1a
Spring rapeseed	6.7b	1.3b	16.2b	4.4b	0.9b	1.2b
-S	8.5a	1.5	17.7	7.5b	1.3	1.3b
+S	8.0b	1.5	17.9	8.5a	1.3	1.9a
Straw						
Winter rapeseed	5.1b	0.9b	15.0a	10.9a	0.8b	2.2b
Spring rapeseed	8.5a	1.5a	12.3b	10.6b	1.4a	2.5a
-S	6.9a	1.2	12.9b	10.5b	1.1	2.1b
+S	6.6b	1.2	14.4a	10.9a	1.1	2.6a
Oil cake						
Winter rapeseed	44.2b	10.0b	13.0a	3.7a	4.2	3.3b
Spring rapeseed	51.4a	11.2a	12.0b	2.9b	4.1	3.9a
-S	47.7	10.5b	12.2b	3.1b	4.0b	3.5b
+S	47.9	10.8a	12.8a	3.4a	4.3a	3.8a

* values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test

gnificantly more (by around 0.2 g kg^{-1} DM) phosphorus in fertilized treatments, whereas phosphorus levels in spring rapeseed roots did not vary significantly in response to fertilization. In fertilized treatments, potassium concentrations decreased (by 0.7 g kg^{-1} DM) in winter rapeseed roots, but increased (by 1.2 g kg^{-1} DM) in spring rapeseed roots (Figure 1).

Straw

In a study by Spiak et al. (2007), winter rapeseed straw accumulated significant amounts of calcium (around 19.9 g kg^{-1} DM), and the concentrations of the remaining macronutrients were determined at 9.5 (K), 4.3 (N), 0.8 (P) and 0.8 (Mg) g kg^{-1} DM (Spiak et al. 2007). The straw of spring rapeseed is also an abundant source of calcium (11.3 g kg^{-1} DM on average), but it contains less of this element than winter rapeseed. The concentrations of the remaining macronutrients were similar in the compared rapeseed forms (Spiak et al. 2007, Ciubak 2009). In our study, the differences in the macronutrient content of straw between winter and spring rapeseed were less unidirectional than those observed in root residues (Table 2). Potassium and magnesium were the only macronutrients noted in higher quantities in the straw of winter rapeseed than spring rapeseed (by 2.7 and 0.3 g kg^{-1} DM, respecti-

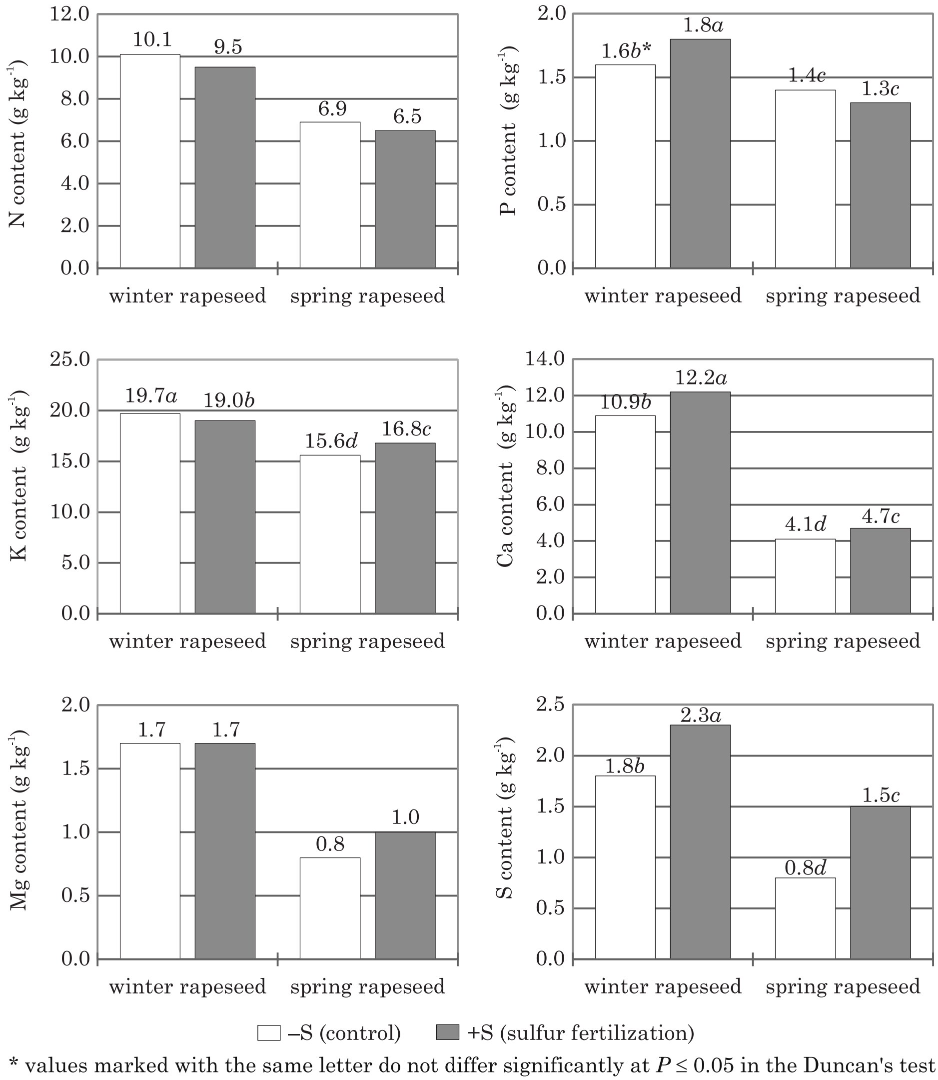
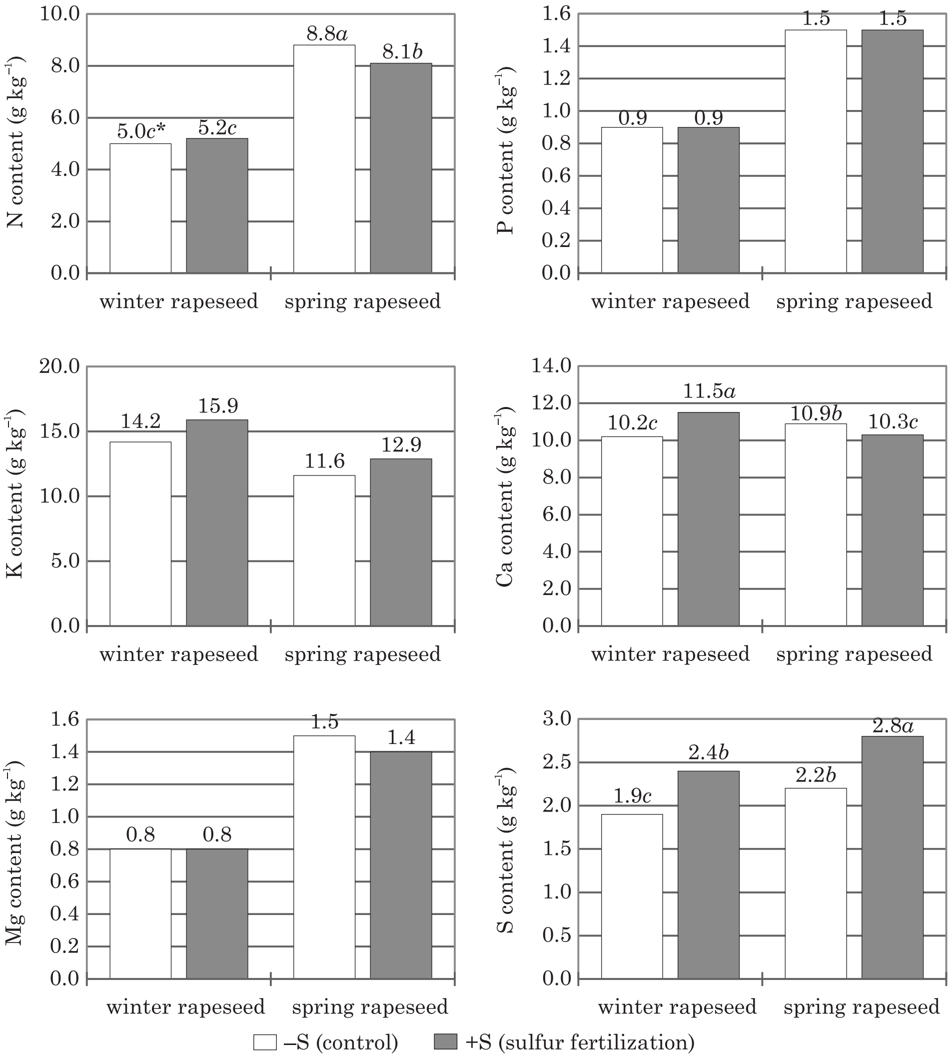


Fig. 1. The effect of sulfur fertilization on the macronutrient content of root residues (roots + stubble) of winter and spring rapeseed (rapeseed form × sulfur fertilization interaction) in 2005-2008

vely). The remaining macronutrients (N, P, Ca and S) were reported in higher concentrations in spring rapeseed straw than in winter rapeseed straw (Table 2).

Sulfur fertilization significantly differentiated nitrogen, potassium, calcium and sulfur concentrations in the straw of both rapeseed forms, but it did not induce any changes in phosphorus and magnesium levels (Table 2). In the work of Podleśna (2004), sulfur fertilizers also had a weak effect on phosphorus and magnesium levels in winter rapeseed straw. In our study, the application of sulfur fertilizer at optimal doses for winter and spring rapeseed led to a significant increase in the potassium (by 1.7 and 1.3 g kg^{-1} DM, respectively) and sulfur (by 0.5 and 0.6 g kg^{-1} DM, respectively) content of straw (Table 2, Figure 2). Sulfur fertilization had a different effect on nitrogen and calcium levels in the straw of winter and spring rapeseed. The applied fertilizers significantly increased (by approximately 1.3 g kg^{-1} DM) calcium concentrations, but did not affect nitrogen levels in winter rapeseed



* values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test

Fig. 2. The effect of sulfur fertilization on the macronutrient content of straw of winter and spring rapeseed (rapeseed form× sulfur fertilization interaction) in 2005-2008

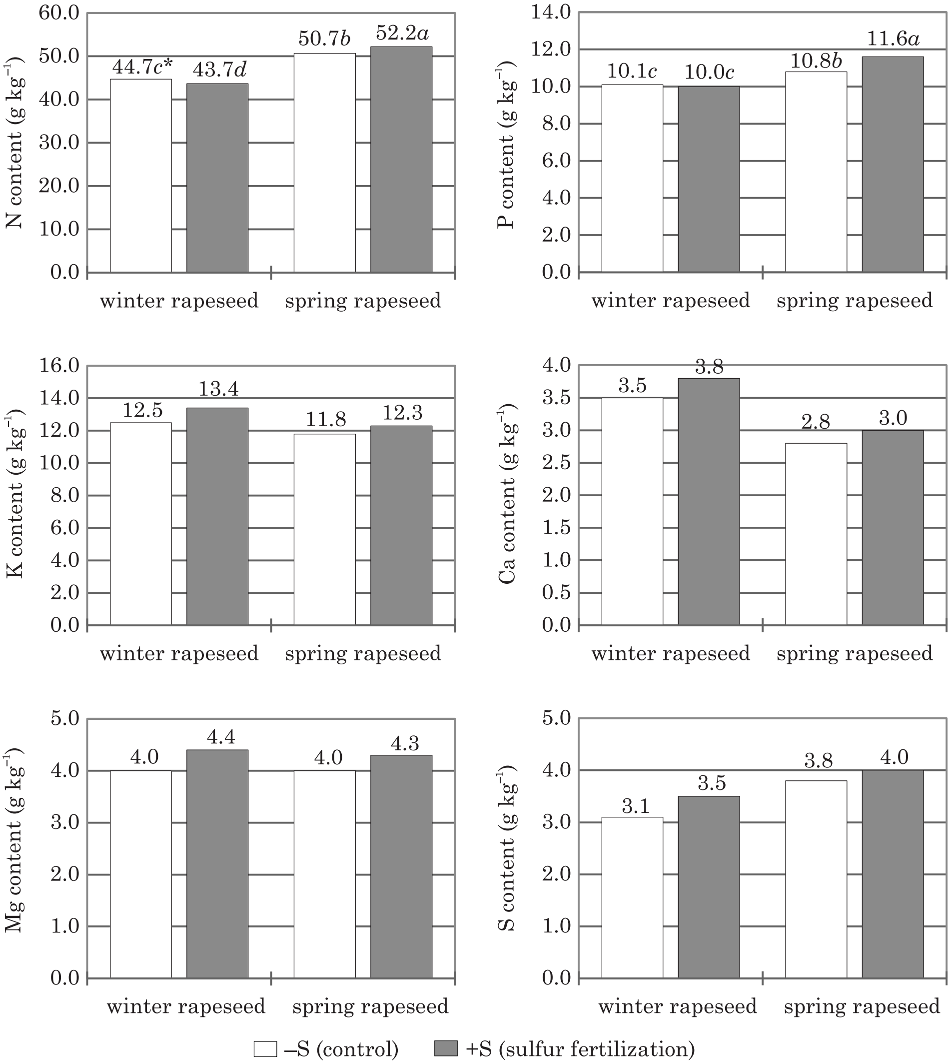
straw. In spring rapeseed, sulfur fertilization significantly lowered the nitrogen and calcium content of straw by 0.7 and 0.6 g kg^{-1} DM, respectively (Figure 2). In a study by Podleśna (2004), sulfur fertilizers applied to soil at 80-100 kg ha^{-1} in autumn led to a significant increase in nitrogen (by 1.0 g kg^{-1} DM) and calcium (by 0.13 g kg^{-1} DM) concentrations in straw.

Oil cake

The potential fertilizing value of oil-free residues of winter rapeseed can be attributed to high concentrations of nitrogen (32.0-48.0 g kg^{-1} DM), potassium (7.7-11.1 g kg^{-1} DM), phosphorus (approximately 7.4-9.0 g kg^{-1} DM), sulfur (5.2-9.2 g kg^{-1} DM) and calcium (4.8-6.1 g kg^{-1} DM) (Podleśna 2004, Kalembasa, Adamiak 2010).

The oil cake and meal of spring oilseed plants are generally more macronutrient abundant compared with winter rapeseed. In a study by Malarz (2008), spring rapeseed meal contained 57.4 to 68.8 N kg^{-1} DM. In the work of (Jankowski et. al. 2015), oil-free residues of spring rapeseed accumulated approximately 42 g N kg^{-1} DM. An analysis of the chemical composition of oil-free residues of winter rapeseed (Podleśna 2004) and spring rapeseed (Bell et al. 1999) clearly indicates that the spring form is richer in P, Ca and Mg than the winter form. In our study, spring rapeseed oil cake contained more nitrogen (by 7.2 g kg^{-1} DM), phosphorus (1.2 g kg^{-1} DM) and sulfur (by 0.6 g kg^{-1} DM) on average than winter rapeseed oil cake. Winter rapeseed oil cake was characterized by significantly higher concentrations of potassium (by 1.0 g kg^{-1} DM) and calcium (by 0.8 g kg^{-1} DM) than spring rapeseed oil cake (Table 2).

In spring rapeseed treatments, sulfur fertilization significantly increased the concentrations of all analyzed macronutrients in oil cake (Table 2, Figure 3). Sulfur fertilizers applied to winter rapeseed contributed to a significant decrease in the nitrogen content of oil cake (by 1.0 g kg^{-1} DM), but did not lead to significant differences in its phosphorus levels (Fig. 2). The concentrations of the remaining macronutrients (K, Ca, Mg and S) increased in winter rapeseed oil cake in response to sulfur fertilization (Table 2, Figure 3). In a study by Podleśna (2004), sulfur fertilizers exerted a much weaker effect on the macronutrient content of winter rapeseed than in our experiment. In the cited study, nitrogen and sulfur concentrations increased significantly (by 2.2 and 0.8 g kg^{-1} DM, respectively) in winter rapeseed in response to sulfur fertilizer applied at 80-100 kg S ha^{-1} in autumn. Sulfur fertilization did not lead to significant differences in the content of the remaining macronutrients (P, K, Ca, Mg) in winter rapeseed (Podleśna 2004). The reason of weaker response of sulfur fertilizer on content remaining macronutrients in winter rapeseed in Podleśna (2004) trial was the date of sulfur application. The applied complete sulfur dose (as potassium sulfate, simple superphosphate and ammonium sulfate) was applied before sowing under conditions of well-drained soil classified to the very good rye complex.



* values marked with the same letter do not differ significantly at $P \leq 0.05$ in the Duncan's test

Fig. 3. The effect of sulfur fertilization on the macronutrient content of oil cake of winter and spring rapeseed (rapeseed form × sulfur fertilization interaction) in 2005-2008

CONCLUSIONS

1. The highest nitrogen, phosphorus, magnesium and sulfur concentrations were noted in the oil cake of both rapeseed forms. Potassium levels were the highest in the root residues of winter and spring rapeseed. Winter rapeseed accumulated the highest amounts of calcium in root residues, and spring rapeseed – in straw.

2. Macronutrient concentrations were higher in the roots of winter rapeseed than in the roots of spring rapeseed. Sulfur fertilizers applied to soil decreased nitrogen levels and increased calcium and sulfur concentrations in the roots of both rapeseed forms, whereas phosphorus levels increased only in the roots of winter rapeseed. Sulfur fertilization decreased the potassium content of winter rapeseed roots, but increased potassium levels in spring rapeseed roots.

3. The straw of spring rapeseed was richer in nitrogen, phosphorus, calcium and sulfur than the straw of winter rapeseed. Potassium and magnesium concentrations were higher in winter rapeseed straw. Sulfur fertilization significantly increased the potassium and sulfur content of straw of both rapeseed forms. In winter rapeseed treatments, sulfur fertilization contributed to a significant increase in the calcium content of straw, but it did not influence nitrogen concentrations. Fertilization significantly decreased nitrogen and calcium concentrations in spring rapeseed straw.

4. Spring rapeseed oil cake was significantly richer in nitrogen, phosphorus and sulfur than winter rapeseed oil cake. Potassium and calcium concentrations were higher in winter rapeseed oil cake. Sulfur fertilization significantly increased the concentrations of all the analyzed macronutrients in spring rapeseed oil cake. In winter rapeseed, sulfur fertilization increased the content of all macronutrients (except for nitrogen and phosphorus) in oil cake.

REFERENCES

Batalin M. 1962. *A study on postharvest residues of agricultural crops in a stand.* Rocz. Nauk Rol., D, 98: 1-154. (in Polish)

Bednarek W., Tkaczyk P., Dresler S. 2009. *Yields of winter wheat in dependence on some soil properties and agricultural measures.* Acta Agroph., 14(2): 263-273. (in Polish)

Bell J.M., Rakow G., Downey R.K. 1999. *Mineral composition of oil-free seeds of Brasica napus, B. rapa and B. juncea as affected by location and year.* Can. J. Anim. Sci, 79: 405-408.

Blaylock M.J., Salt D.E., Dushenkov S., Zakharova O., Gussman C., Kapulnik Y., Ensley B.D., Raskin I. 1997. *Enhanced accumulation of Pb in Indian mustard by soil-applied chelating agents.* Environ. Sci. Technol., 31: 860-865.

Chaignon V., Bedin F., Hinsinger P. 2002. *Copper bioavailability and rhizosphere pH changes as affected by nitrogen supply for tomato and oilseed rape cropped on an acidic and a calcareous soil.* Plant Soil, 243: 219-228.

Chlopecka A., Bacon J. R., Wilson M. J., Kay J. 1996. *Forms of cadmium, lead, and zinc in contaminated soils from southwest Poland.* J. Environ. Qual., 25: 69-79.

Ciubak J. 2009. *Effect of multicomponent mineral fertilizers on the size and quality of crop plants for energy purposes, and some indicators of soil fertility.* A PhD dissertation at the West Pomeranian University of Life Sciences in Szczecin, <http://212.14.41.9/Content/2293/rozprawa%20doktorska%20j.ciubak.pdf?handler=pdf>, 11.2014 (in Polish)

Cui Y., Wang Q., Dong Y., Li H., Christie P. 2004. *Enhanced uptake of soil Pb and Zn by Indian mustard and winter wheat following combined soil application of elemental sulphur and EDTA.* Plant Soil, 261: 181-188.

Jankowski K., Kijewski Ł., Skwierawska M., Krzebietke S., Mackiewicz-Walec E. 2014*a*. *The effect of sulfur fertilization on the concentrations of copper, zinc and manganese in the roots,* *straw and cake of rapeseed (Brassica napus* L. ssp. *oleifera* Metzg*).* J. Elem., 19(2): 433-446. DOI: 10.5601/jelem.2013.18.4.552

Jankowski K.J., Budzyński W.S., Kijewski Ł., Dubis B., Lemański M. 2014*b*. *Flour quality, the rheological properties of dough and the quality of bread made from the grain of winter wheat grown in a continuous cropping system*. Acta Sc. Pol., Agric., 13(3): 3-18.

Jankowski K.J., Budzyński W.S., Kijewski Ł., Klasa A. 2014*c*. *Concentrations of copper, zinc and manganese in the roots, straw and oil cake of white mustard (Sinapis alba* L.*) and Indian mustard (Brassica juncea (*L.*)* Czern. et Coss.*) depending on sulfur fertilization*. Plant Soil Environ., 60(8): 364-371.

Jankowski K.J., Budzyński W.S., Kijewski Ł., Zając T. 2015. *Biomass quality of Brassica oilseed crops in response to sulfur fertilization*. Agron. J., 4. DOI: 10.2134/agronj14.0386

Jasińska Z., Kotecki A., Kozak M., Malarz W. 2002. *Fertilizing value of winter rape harvest residue*. Pam. Puł., 130: 309-319. (in Polish)

Kaczor A., Brodowska M. 2003. *Effect of liming and silphur fertilization on the growth and yielding of spring forms of wheat and rape.* Part II. *Spring rape*. Acta Agroph., 1(4): 661-666. (in Polish)

Kalembasa S., Adamiak E. A. 2010. *Determination of chemical composition of rapeseed cake*. Acta Agroph., 15(2): 323-332.

Kotecki A., Kozak M., Malarz W. 2001. *Manurial value of wheat and winter rape straw*. Zesz. Nauk. AR Wroc., Rol., 77: 7-73. (in Polish)

Malarz W. 2008. *Effects of some agrotechnical factors on the development and yield quality of spring rape cultivars*. Zesz Nauk. UP we Wrocławiu 562, Rozpr., 251: 1-84. (in Polish)

Malhi S.S., Lemke R. 2007. *Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emission in a second 4-yr rotation cycle*. Soil Tillage Res., 96: 269-283.

Malicki L. 1997. *Importance of post-harvest residues in crop rotation*. Acta Acad. Agricult. Tech. Olst. Agric., 64: 57-66. (in Polish)

Podleśna A. 2004. *The effect of sulfur fertilization on concentration and uptake of nutrients by winter oilseed rape*. Rośliny Oleiste - Oilseed Crops, 25(2): 627-636. (in Polish)

Salt D.E., Blaylock M.J., Kumar N.P.B.A., Dushenkov V., Ensley B.D., Chet I., Raskin I. 1995. *Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants*. Biotechnology, 13: 468-474.

Sieling K., Stahl K., Winkelmann C., Christen O. 2005. *Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany*. Eur. J. Agron., 22: 71-84.

Spiak Z., Piszcz U., Zbroszczyk T. 2007. *Disposition of nutrients in seeds and straw of selected winter rape cultivars*. Part I. *Macronutrients*. Zesz. Nauk. AR Wroc., Rol., 90(553): 93-106. (in Polish)

Szczebiot M., Ojczyk T. 2002. *Fertilization value of post-harvest residues of oil crops for winter wheat*. Fragm. Agron., 2: 198-206. (in Polish)

Troczyńska J. 2005. *The myrosinase-glucosinolates system – its character and functions in plant*. Rośliny Oleiste – Oilseed Crops, 26(1): 51-64. (in Polish)

Wesołowski M., Dąbek-Gad M., Maziarz P. 2007. *The effect of forecrop species and herbicide treatment on the yield of winter wheat*. Fragm. Agron., 4: 240-246. (in Polish)

Wyszkowski M., Wyszkowska J. 2004. *Chemical composition of spring rape and white mustard and the enzymactic activity of soil contaminated with Treflan 480 EC*. Ann. UMCS, Sect. E, 59(4): 1631-1638. (in Polish)

Zukalová H., Vašák J. 2002. *The role and effects of glucosinolates of Brassica species – a review*. Rostl. Vyroba, 48(4): 175-180.