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Content and yield of oil in spring rape seeds in conditions of nitrogen and sulphur fertilization

Zawartość i wydajność tłuszczu z nasion rzepaku jarego w warunkach nawożenia azotem i siarką

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Abstract

A three-year field experiment was conducted in northern Poland on degraded black soil, valuation class IIIb, with very high content of phosphorus and potassium, low content of sulphur, and neutral pH. The experiment was carried out in a split-block design with two factors, in four replications. The aim of the study was to evaluate the effect of different application rates of nitrogen (factor A: 0, 60, 120 and 180 kg N·ha^{-1}) and sulphur (factor B: 0, 20 and 60 kg S·ha^{-1}), taking into account different means of its application (soil application before sowing and foliar application of sulphur) on the oil content and yield in seeds of the Star cultivar of rapeseed. Somewhat higher oil content and yield were observed in the case of soil application of sulphur than for foliar application. In each growing season nitrogen and sulphur applied independently significantly increased the oil content and yield from the seeds of spring rapeseed as compared to the control. Irrespective of the means of application, application of sulphur together with nitrogen generally resulted in higher oil content and yield than application of either of these nutrients alone, but their interaction was not confirmed statistically. The observed beneficial effect of sulphur applied alone and together with nitrogen on important criteria of spring rapeseed quality substantiates the need to include sulphur in fertilization of this species.

Keywords: application methods of sulphur, *Brassica napus* L., content of oil, nitrogen fertilization, spring oilseed rape, sulphur fertilization, yield of oil

Abstrakt

W północnej Polsce przeprowadzono trzyletnie ścisłe doświadczenie polowe na czarnej ziemi zdegradowanej, klasy bonitacyjnej IIIb, o bardzo wysokiej zasobności w fosfor i potas, niskiej – w siarkę oraz o obojętnym odczynie. Doświadczenie realizowano w czterech powtórzeniach, w układzie równoważnych bloków z dwoma czynnikami. Celem badań była ocena wpływu zróżnicowanych dawek azotu (czynnik A – 0, 60, 120 i 180 kg N·ha^{-1}) i siarki (czynnik B – 0, 20 i 60 kg S·ha^{-1}) z uwzględnieniem różnych sposobów jej aplikacji (doglebowo przedsiewnie i dolistnie), na zawartość i wydajność tłuszczu z nasion rzepaku jarego odmiany Star. Wykazano, że nieco wyższa zawartość i wydajność tłuszczu charakteryzowała nasiona rzepaku jarego nawożonego siarką doglebowo niż dolistnie. Azot i siarka stosowane niezależnie od siebie (pojedynczo) w każdym sezonie wegetacyjnym istotnie zwiększały zawartość i wydajność tłuszczu z nasion rzepaku jarego w porównaniu z kontrolą. Niezależnie od sposobu aplikacji, zastosowanie siarki łącznie z azotem, pozwalało na ogół uzyskać wyższą zawartość i wydajność tłuszczu z nasion rzepaku niż wyłączna aplikacja badanych składników, jednak nie potwierdzono statystycznie współdziałania tych składników.

Słowa kluczowe: *Brassica napus* L., nawożenie azotem, nawożenie siarką, plon tłuszczu, rzepak jary, sposoby aplikacji siarki, zawartość tłuszczu

Streszczenie rozszerzone

Z uwagi na postępujący niedobór siarki w polskich glebach oraz ważny udział tego składnika w metabolizmie azotu, podjęto badania, których celem była ocena wpływu zróżnicowanych dawek azotu i siarki z uwzględnieniem różnych sposobów jej aplikacji, na zawartość i wydajność tłuszczu z nasion rzepaku jarego. Podstawą badań było trzyletnie doświadczenie polowe realizowane na czarnej ziemi zdegradowanej, należącej do kompleksu pszennego wadliwego, klasy bonitacyjnej IIIb. Gleba posiadała uregulowane stosunki wodne, obojętny odczyn, bardzo wysoką zasobność w przyswajalne formy fosforu i potasu, średnią zasobność w magnez i niską – w siarkę. Doświadczenie realizowano w układzie równoważnych bloków z dwoma czynnikami, w czterech powtórzeniach. Badanym gatunkiem był rzepak jary odmiany populacyjnej Star (DLF Trifolium, Dania). Na jednym polu zlokalizowano w sąsiedztwie dwie części doświadczenia z różnymi sposobami aplikacji siarki, a pomiędzy nimi usytuowano wspólny obiekt kontrolny, bez nawożenia siarką i azotem. W obydwu częściach doświadczenia azot i siarkę aplikowano w jednakowych formach i w takich samych dawkach, jednak w pierwszej – siarkę stosowano przedsiewnie (doglebowo), w drugiej – pogłównie (dolistnie). Doświadczenie było dwuczynnikowe, zakładano je w czterech powtórzeniach, a powierzchnia poletek do zbioru wynosiła 18 m^2. Stosowano zróżnicowane dawki azotu (czynnik A – w kg N·ha^{-1}: 0, 60, 120, 180) i siarki (czynnik B – w kg S·ha^{-1}: 0, 20, 60). W obydwu blokach doświadczalnych nawożono azotem w formie saletry amonowej, w dawkach dzielonych po 60 kg N·ha^{-1}. W obiektach, w których siarkę stosowano przedsiewnie (doglebowo), obie dawki wysiano w tym samym czasie, po włókowaniu pola. W obiektach, w których siarka była aplikowana pogłównie (dolistnie), dawki dzielono, stosując jednorazowo 20 kg S·ha^{-1} w pełni wschodów (BBCH 10-15), a na poletkach z dawką 60 kg S·ha^{-1} dodatkowo – 20 kg S·ha^{-1} po wykształceniu łodygi (BBCH 30-39) oraz 20 kg S·ha^{-1} na początku kwitnienia (BBCH 57-62). Składnik ten aplikowano w formie bezwodnego siarczanu sodowego (22,5% S). Poza opisanym zróżnicowaniem terminów stosowania siarki, wszystkie pozostałe elementy agrotechniki były jednakowe w całym doświadczeniu.

Zawartość tłuszczu w nasionach rzepaku jarego była cechą stosunkowo stabilną, gdyż jego ilościowe zróżnicowanie w zależności od roku badań, było niewielkie. Na kształtowanie zawartości tłuszczu w nasionach w obydwu doświadczeniach istotnie wpływało nawożenie zarówno siarką, jak i azotem, natomiast w żadnym z lat badań nie potwierdzono statystycznie współdziałania tych składników. W każdym z sezonów wegetacyjnych zawartość tłuszczu w nasionach roślin nawożonych wyłącznie azotem (bez siarki) lub samą siarką (bez azotu) była istotnie wyższa niż w nasionach roślin z obiektu kontrolnego. Pod wpływem wyłącznego nawożenia siarką stwierdzono nieco wyższą zawartość tłuszczu w nasionach roślin z doświadczenia z doglebową aplikacją siarki niż dolistną (różnica średnio – 1,4%). W przypadku doglebowego stosowania siarki nie wykazano istotnej różnicy w działaniu dawek 20 i 60 kg S·ha^{-1}, a w doświadczeniu z dolistną aplikacją na ogół istotnie korzystniej od 60 kg S·ha^{-1} działała dawka 20 kg S·ha^{-1}.

Łączna aplikacja azotu i siarki miała bardziej korzystny wpływ na zawartość tłuszczu w nasionach rzepaku jarego niż niezależne stosowanie tych składników. W obiektach z doglebową aplikacją siarki najwyższą zawartość tłuszczu (średnio dla trzech lat badań) uzyskano po zastosowaniu 60 kg N·ha^{-1} i 60 kg S·ha^{-1}. W doświadczeniu, w którym siarkę stosowano dolistnie, optymalna okazała się kombinacja 60 kg N·ha^{-1} i 20 kg S·ha^{-1}.

We wszystkich latach wyłączne stosowanie azotu (bez siarki) lub wyłączna aplikacja siarki (bez azotu) powodowały istotne zwiększenie wydajności tłuszczu z nasion rzepaku jarego w porównaniu z kontrolą. Różnice dla 60, 120 i 180 kg N·ha^{-1} średnio wynosiły odpowiednio: 35%, 46,7% i 56,7%. Wydajność tłuszczu z nasion była nieco większa w doświadczeniu z doglebową aplikacją siarki niż z dolistnym stosowaniem tego składnika – różnica średnio dla trzech lat badań wynosiła 1,9%. Dawką siarki, która pozwalała osiągnąć istotnie najwyższą wydajność tłuszczu, niezależnie od sposobu aplikacji, było 20 kg S·ha^{-1}.

Jednoczesne stosowanie azotu i siarki było korzystniejsze dla wydajności tłuszczu w nasionach rzepaku niż pojedyncza aplikacja każdego z tych składników, co dowodzi, że uwzględnienie siarki w nawożeniu rzepaku zwiększa efektywność nawozów azotowych. Wśród badanych kombinacji nawozowych najwyższą wydajność tłuszczu w obiektach z doglebowym nawożeniem siarką uzyskano po zastosowaniu 180 kg N·ha^{-1} i 60 kg S·ha^{-1}, a w doświadczeniu z dolistną jej aplikacją w wyniku zastosowania 120 kg N·ha^{-1} i 20 kg S·ha^{-1}. Należy podkreślić, że pomiędzy działaniem 120 i 180 kg N·ha^{-1} na tle siarki nie było na ogół istotnych różnic.

Wykazany korzystny wpływ siarki stosowanej osobno i razem z azotem na ważne kryteria jakości plonu rzepaku jarego, jakimi są zawartość i wydajność tłuszczu w nasionach, uzasadnia konieczność uwzględniania siarki w nawożeniu tego gatunku.

Introduction

Production of oilseed has shown an upward trend for years, due to the globally growing demand for food and for renewable energy (Bartkowiak-Broda et al., 2005). Efforts to improve the nutritional status of the growing world population and the development of biofuel production cause the raising demand for vegetable oils (Kaczor et al., 2003). Moreover, the development of animal production using modern nutritional technologies contributes to the demand for oilseed meals (Rudko, 2011; Mansoori, 2012). These tendencies are also observed in the case of rapeseed, which cultivation in Europe in 2014 covered an area of 9.11 million ha, yielding and harvest of 28.9 million tonnes (FAOSTAT, 2017). The differences in comparison with the year 2000 are 97.3% and 146%, respectively. In Poland, rapeseed production in recent years has become the fastest growing area of crop production. The share of rapeseed in the national crop distribution has grown from under 4% before accession to the European Union (2004 year) to 7-9% in the last five years. This dynamic growth of rapeseed production was determined by EU policy creating enormous demand for this raw material, which is used for production of methyl esters constituting biocomponents of diesel fuel (Bartkowiak-Broda et al., 2005). Biofuel production in Poland currently consumes twice as much rapeseed oil as the food industry.

In Poland the acreage of oilseed crops is dominated by winter rapeseed (95-97%). Spring rapeseed has a small share in the crop distribution, but in the conditions of dry, cold winters it may be the only aftercrop used when the winter rapeseeds froze in winter, particularly when herbicides applied in autumn rule out the cultivation of spring cereals.

Many macronutrients are needed for rapeseed to develop properly – primarily nitrogen, but also sulphur, an element for which species of the *Brassiccacae* family have particularly high quantitative demands (Rudko, 2011; Mansoori, 2012; Barczak et al., 2016). Despite the numerous sources of sulphur in the soil (post-harvest residues mixed in with the topsoil, precipitation, or fertilizers), symptoms of sulphur deficiency are noted in the soils of many parts of the world (Walker and Dawson, 2003; Morris, 2007; Camberato et al., 2012), including Poland (Siebielec et al., 2012). This is mainly due to the reduction in SO_x emissions into the atmosphere from industrial sources (Morris, 2007; Klikocka, 2010; Messick, 2013), restrictions on the use of natural and mineral fertilizers containing sulphur (Rutkowska et al., 2009), and changes in the selection of available fertilizers. In these conditions it becomes necessary to include sulphur in crop fertilization (Walker and Dawson, 2003; Podleśna and Strobel, 2009; Barczak, 2010). In view of the important role of sulphur and nitrogen in the metabolism of plants of the *Brassicaceae* family and the increasing interest in sulphur as a fertilizer component, a study was undertaken to determine the effect of varied rates and means of sulphur application together with nitrogen on the oil content and yield of spring rapeseed oil.

Material and methods

In the village of Kaźmierzewo (52°73' N; 18°88' E, Kuyavian-Pomeranian Voivodeship, northern Poland) a three-year field experiment was conducted on degraded black soil, valuation class IIIb (defective wheat complex). The soil had a regulated water regime, neutral pH, very high content of available phosphorus and potassium, intermediate magnesium content, and low sulphur content (Table 1). The experiment was carried out in a split-block design with two factors, in four replications. The species studied was spring rapeseed (*Brassica napus* L.) of the open-pollinated variety Star (DLF Trifolium, Denmark). The fore crop for rapeseed in each growing season was sugar beet.

Two parts of an experiment with different sulphur application methods and control object were located on one field. In both parts of this experiment nitrogen and sulphur were applied in the same forms and at the same rates, but in the first of them sulphur was applied to the soil before sowing, and in the second – as top dressing (foliar application). Experiment had two factors and were set up in four replications in a split-block design. The area of the plots for harvest was 18 m^2.

Different application rates of nitrogen – factor A (kg $N \cdot ha^{-1}$): 0, 60, 120, 180 and sulphur – factor B (kg $S \cdot ha^{-1}$): 0, 20 and 60 were used. In both experiments nitrogen was applied in split applications of 60 kg $N \cdot ha^{-1}$. In all treatments with nitrogen fertilizer the first portion was applied before sowing in the form of ammonium nitrate containing 34% N (17% $N\text{-}NH_4^+$ and 17% $N\text{-}NO_3^-$) with an addition of 2% CaO, 4% MgO and 0.2% boron. In the case of each type of fertilizer 30 kg $N \cdot ha^{-1}$ was applied. In the treatments with 120 kg $N \cdot ha^{-1}$ nitrogen was also applied 3-4 weeks before flowering (second application – BBCH 50-55), and in the treatments with 180 kg $N \cdot ha^{-1}$, before flowering (second application BBCH 50-55) and at the start of flowering (third application – BBCH 60-62). The second and third portions were applied exclusively in the form of ammonium nitrate.

Sulphur application to the soil before sowing was done at the same time in the case of both amounts of sulphur – following levelling of the field. The foliar application of sulphur was split: in all fertilized treatments 20 kg $S \cdot ha^{-1}$ was applied once at emergence (BBCH 10-15), and in the treatments with 60 kg $S \cdot ha^{-1}$, 20 kg $S \cdot ha^{-1}$ was additionally applied after stem formation (BBCH 30-39) and 20 kg $S \cdot ha^{-1}$ at the start of flowering (BBCH 57-62). Apart from these differences in sulphur application times, all other elements of the agrotechnical procedures were identical in the two parts of experiment. Sulphur was applied in the form of anhydrous sodium sulphate (22.5% S).

Prior to winter ploughing a compound fertilizer was applied, with 120 kg $K_2O \cdot ha^{-1}$, 60 kg $P_2O_5 \cdot ha^{-1}$ and 48 kg $MgO \cdot ha^{-1}$.

The field experiment was performed in an area with a mean annual air temperature of 7.8 °C and precipitation generally not exceeding 450 mm, including about 300 mm per growing period (means for 1949-2009). Field work begins in early April and the growing period generally lasts 205-230 days.

To provide more complete characteristics of the weather conditions in the research period, for the months of the spring rape growing period the Selyaninov hydrothermal coefficient was calculated:

$K = P/0.1\Sigma T$,

where:

P – sum of monthly precipitation in mm

T – sum of monthly air temperature > 0 °C

Calculated values of Selyaninov's coefficient confirmed high variation in weather conditions in the research years (Table 1). The most favourable weather conditions for the growth and development of spring rapeseed were noted in the first year of the study. Systematic showers after sowing, in both April and May, a favourable rain distribution in June and heavy rainfall in July were conducive to rapeseed growth. In

May of the second year rainfall was heavy but its distribution was unfavourable. The rainy first days of the month were followed by a period of nearly four weeks without rainfall, which coincided with the rosette-forming stage.

Heavy rainfall at the end of July and the beginning of August led to lodging, particularly in the treatments with higher application of nitrogen. In the third year of the study, for three consecutive months, beginning in May, a shortage of rainfall was evident. The total rainfall from May to July was only 136 mm (65% of the long-term average for these months), which was expressed as considerably lower values for the Selyaninov index characterizing the weather conditions for this growing season.

Table 1. Sielianinov's coefficient values throughout the researche period as compared with the multi-year means

Tabela 1. Wartości współczynnika Selianinowa w okresie prowadzenia badań polowych w porównaniu ze średnią wieloletnią

Year Rok	Months Miesiące					
	IV	V	VI	VII	IV-VII	V-VI
I	1.68	2	1.65	1.91	1.83	1.8
II	0.98	1.23	1.46	1.81	1.43	1.36
III	2.84	1.05	1.01	0.55	1.14	1.03
Mean for the multi-year Średnia z wielolecia	1.48	1.22	1.41	1.27	1.33	1.32

Threshold values: 0.4<K<0.7 – very dry, 0.7<K<1 – dry, 1<K<1.3 – fairly dry, 1.3<K<1.6 – optimal, 1.6<K<2 – fairly moist, 2<K<2.5 – moist (Skowera and Puła, 2004).
Wartości progowe: 0,4<K<0,7 – okres bardzo suchy, 0,7<K<1 – suchy, 1<K<1,3 – dość suchy, 1,3<K<1,6 – optymalny, 1,6<K<2 – dość wilgotny, 2<K<2,5 – wilgotny (Skowera and Puła, 2004).

Statistical methods

The results of the experiment were subjected to analysis of variance (ANOVA) for split-block designs (Statistica ARSL, 2008). To compare the effects of soil and foliar application of sulphur, was it analysed the relative standard deviations of values for traits in the treatments with sulphur and nitrogen fertilization from the values for these traits in the control without application of these nutrients. Significance of differences between means was determined by Tukey's test.

Results and discussion

Oil content in the spring rapeseeds was relatively stable, ranging on average, depending on the year, from 428 to 438 g·kg^{-1} in the experiment with soil application of sulphur and from 424 to 432 g·kg^{-1} in the experiment with foliar application of sulphur (Table 2). In parts of experiment fertilization with both sulphur and nitrogen significantly influenced the oil content in the rapeseeds, but no interaction of these nutrients was confirmed in any year of the study.

In each of the growing seasons the oil content in the seeds of the plants fertilized with nitrogen alone (without sulphur) was significantly higher than in the seeds of plants grown without nitrogen. The differences with respect to the control, on average for the three years of the study, were 3.3%, 3.1% and 2.9% for 20, 40 and 60 kg N·ha^{-1}, respectively.

Only in the first year was a significantly more beneficial effect of 120 kg N·ha^{-1} observed in comparison to 60 and 180 kg N·ha^{-1}; in the second and third years no differences between application rates were statistically confirmed. Nitrogen is considered to be the nutrient which most strongly determines not only the productivity of rapeseed but also the technological value of its seeds (Bartkowiak-Broda et al., 2005). A study by Mansoori (2012) on winter rapeseed showed that application of 80 kg N·ha^{-1} led to an average 14.1% increase in oil content in the seeds as compared to the control. In a study on mustard by Kumar et al. (2016), oil content increased 8.9% following application of 120 kg N·ha^{-1}. However, many authors (Farahbakhsh et al., 2006; Tomar and Singh, 2007; Podleśna and Strobel, 2009) report a decrease in oil content in rapeseeds following intensive fertilization with this nutrient.

Application of sulphur alone (without nitrogen) led to slightly higher oil content in the seeds of the plants in the experiment with soil sulphur application than in the case of its foliar application; the average difference for the three years of the study was 1.4%. In all years of the study, irrespective of the means of sulphur application, fertilization with this nutrient significantly increased oil content. In the case of soil application, no significant difference was noted in the effect of levels of 20 and 60 kg S·ha^{-1}, but in the experiment with foliar application the effect of 20 kg S·ha^{-1} was generally significantly more favourable than that of 60 kg S·ha^{-1}.

Oil content in rapeseeds is a stable, genetically determined characteristic (Rudko, 2011), but many studies confirm a modifying effect of agrotechnical factors on this trait (Rice, 2007; Malarz et al., 2011), among which sulphur application plays an important role (Sienkiewicz-Cholewa and Kieloch, 2015; Wielebski, 2015; Varényiová et al., 2017). The increased oil content observed following sulphur application is a consequence of increased content of CoA, which is a substrate for lipogenesis. Vitamin H (biotin), which contains this element, is a coenzyme of carboxylases and forms an enzyme system essential for biosynthesis of fatty acids (De Kok et al., 2003). The positive effect of sulphur on acetyl-CoA carboxylase activity is important as well (Fazili et al., 2010).

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Table 2. Oil content in spring rape seeds [g·kg-1]

Tabela 2. Zawartość tłuszczu w nasionach rzepaku jarego [g·kg-1]

[kg N·ha-1]	I year I rok [kg S·ha-1] 0	20	60	Mean Średnia	II year II rok [kg S·ha-1] 0	20	60	Mean Średnia	III year III rok [kg S·ha-1] 0	20	60	Mean Średnia	Mean for the years Średnia z lat 0	20	60	Mean Średnia
Sulphur applied to the soil/Siarka stosowana doglebowo																
0	419	429	430	426	421	436	440	432	413	421	421	418	418	429	430	425
60	431	447	448	442	435	446	448	443	430	435	436	434	432	443	444	440
120	438	451	453	447	432	440	442	438	422	430	432	428	431	440	442	438
180	431	440	443	438	430	439	440	436	428	433	435	432	430	437	439	435
Mean Średnia	430	442	444	438	430	440	443	437	423	430	431	428	428	437	439	435
LSD/NIR$_{(P=0.05)}$	A-5.1, B-4.2, AxB-n.s./n.i.				A-6.0, B-5.2, AxB-n.s./n.i.				A-8.8, B-2.6, AxB-n.s./n.i.				A-3.1, B-2.2, AxB-n.s/n.i.			
Foliar application of sulphur/Siarka stosowana dolistnie																
0	419	425	419	421	421	426	420	422	413	418	413	415	418	423	417	419
60	431	443	432	435	435	445	438	439	43	434	430	431	432	441	433	435
120	438	448	437	441	432	438	432	434	422	430	420	424	431	439	430	433
180	431	435	429	432	430	435	430	432	428	433	420	427	430	434	426	430
Mean Średnia	430	438	429	432	430	436	430	432	423	429	421	424	428	434	427	429
LSD/NIR$_{(P=0.05)}$	A-6.4, B-4.3, AxB-n.s./n.i.				A-4.2, B-3.5, AxB-n.s./n.i.				A-7.5, B-5.6, AxB-n.s./n.i.				A-3.3, B-2.7, AxB-n.s./n.i.			

LSD - Least Significant Difference, n.s. – non significant. NIR - Najmniejsza Istotna Różnica, n.i. – nieistotny.

Numerous studies conducted on oilseed plants in conditions of sulphur deficiency indicate reduced oil content in the seeds (Haneklaus et al., 1999; Fismes et al., 2000). Inclusion of sulphur in fertilization leads to an increase in oil accumulation in rapeseeds (Lošak and Richter, 2003; Farahbakhsh et al., 2006; Mansoori, 2012; Sienkiewicz-Cholewa and Kieloch, 2015). Sulphur application has a beneficial effect on oil synthesis in the case of mustard, as well (Tomar and Singh, 2007; Ray et al., 2015; Kumar et al., 2016). However, in studies conducted in conditions in which plants are well supplied with sulphur, its application does not increase oil content in the seeds (McGrath and Zhao, 1996; Podleśna and Strobel, 2009) or even reduces it (Wielebski, 2006; Malarz et al., 2011). Independent application of nitrogen and sulphur was less beneficial to the oil content in the spring rapeseeds than combined application of these nutrients. In the experiment with soil application of sulphur, the highest oil content in the seeds, on average for the three years of the study, was obtained following application of 60 kg $N \cdot ha^{-1}$ and 60 kg $S \cdot ha^{-1}$. In the experiment with foliar application of sulphur, the treatment with 60 kg $N \cdot ha^{-1}$ and 20 kg $S \cdot ha^{-1}$ proved optimal.

Sulphur fertilization of oilseed plants not only affects the oil content in the seeds but also modifies the oilty acid profile. Studies on the response of spring and winter rapeseed (Rotkiewicz et al., 1996; Szulc et al., 2003) and mustard (Ahmad and Abdin, 2000) to sulphur fertilization have shown that it can reduce the content of oleic acid ($C_{18:1}$), the primary unsaturated fatty acid in the oil, while increasing the total oil content. Ahmad and Abdin (2000) reported that appropriate supply of sulphur to plants reduces conversion of oleic acid ($C_{18:1}$) to erucic acid ($C_{22:0}$), beneficially changing the ratio of saturated to unsaturated acids, and thus improving the quality of the oil.

The yield of oil from the spring rapeseeds, calculated as the product of its content in the seeds and the size of the seed yield, was somewhat greater in the experiment with soil application of sulphur than in the case of foliar application; the mean difference for the three years of the study was 1.9% (Table 3). In each year the sole use of nitrogen (without sulphur) and the sole application of sulphur (without nitrogen) caused a significant increase in the oil yield from the seeds. The differences for 60, 120 and 180 kg $N \cdot ha^{-1}$ in relation to the control were 35.1%, 46.8% and 56.8%, respectively. In each growing season application of sulphur alone was more efficient when it was applied to the soil than in the case of foliar application (mean difference 6%). The level of sulphur that led to the highest oil yield, irrespective of the means of application, was 20 kg $S \cdot ha^{-1}$.

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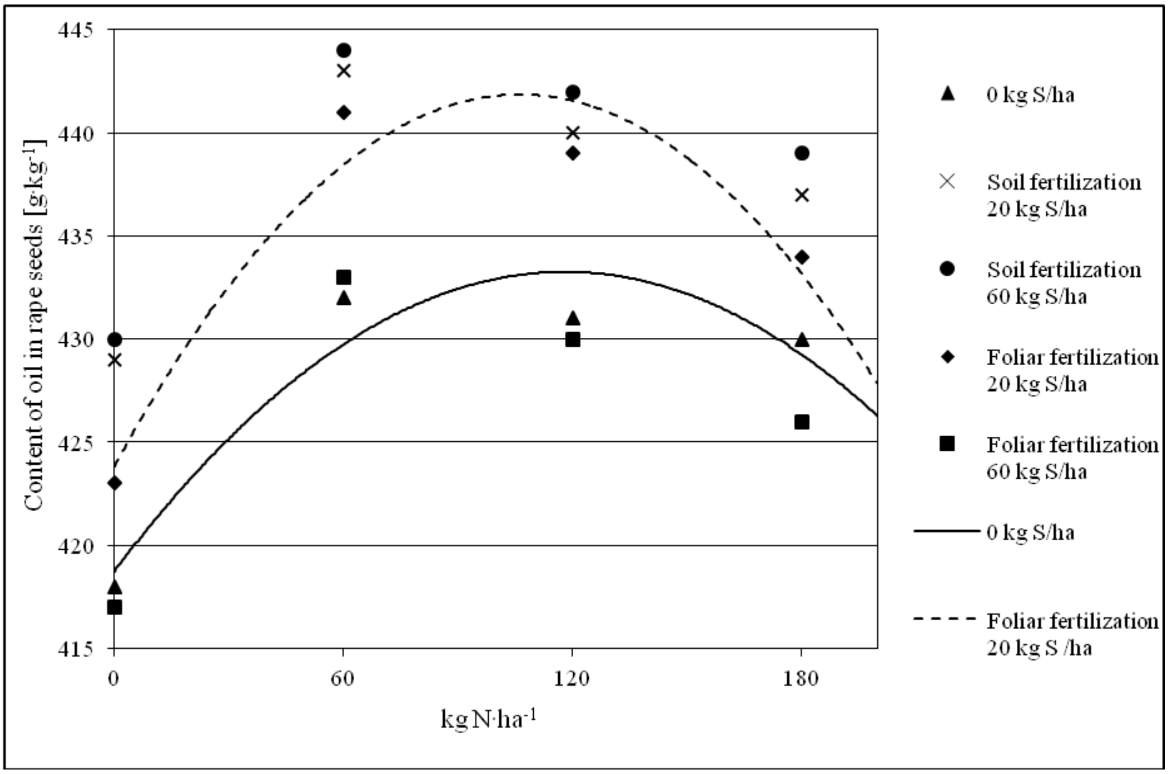
Table 3. Oil yield in spring rape seeds [kg·ha^{-1}]

Tabela 3. Plon tłuszczu nasion rzepaku jarego [kg·ha^{-1}]

[kg N·ha^{-1}]	I year I rok				II year II rok				III year III rok							
	[kg S·ha^{-1}]			Mean Średnia	[kg S·ha^{-1}]			Mean Średnia	[kg S·ha^{-1}]			Mean Średnia	Mean for the years Średnia z lat			Mean Średnia
	0	20	60		0	20	60		0	20	60		0	20	60	
Sulphur applied to the soil/Siarka stosowana doglebowo																
0	951	1,287	1,195	1,141	636	924	832	795	541	720	695	652	710	977	908	863
60	1,276	1,515	1,644	1,476	870	1,057	1,151	1,023	727	770	820	773	959	1,111	1,203	1,090
120	1,445	1,750	1,812	1,667	933	1,073	1,145	1,051	756	800	864	805	1,042	1,202	1,265	1,169
180	1,496	1,628	1,732	1,616	1,079	1,159	1,170	1,133	762	818	914	829	1,113	1,199	1,270	1,193
Mean/Średnia	1,290	1,543	1,594	1,472	877	1,052	1,076	1,001	694	778	823	766	954	1,120	1,160	1,077
LSD/NIR$_{(P=0.05)}$	A-122.1, B-111, AxB-n.s./n.i.				A-98.3, B-87.2, AxB-n.s./n.i.				A-96.3, B-78.9, AxB-87.2				A-64.5, B-55.6, AxB-n.s./n.i.			
Foliar application of sulphur/Siarka stosowana dolistnie																
0	951	1,245	1,077	1,090	636	882	731	747	541	673	586	602	710	931	797	814
60	1,276	1,480	1,590	1,449	870	1,135	1,038	1,014	727	872	727	776	959	1,159	1,118	1,079
120	1,445	1,555	1,774	1,592	933	1,261	1,050	1,081	755	933	781	823	1,042	1,246	1,194	1,160
180	1,496	1,653	1,656	1,603	1,079	1,192	1,122	1,132	762	883	794	811	1,113	1,242	1,189	1,179
Mean/Średnia	1,290	1,485	1,519	1,430	877	1,116	985	994	694	841	724	750	954	1,147	1,075	1,056
LSD$_{(P=0.05)}$	A-139, B-111.4, AxB-142.6				A-105.8, B-94.2, AxB-112.8				A-96.1, B-78.2, AxB-n.s./n.i.				A-75.2, B-49.5, AxB-n.s./n.i.			

LSD - Least Significant Difference, n.s. – non significant. NIR - Najmniejsza Istotna Różnica, n.i. – nieistotny.

Simultaneous application of nitrogen and sulphur was more beneficial for oil yield in the rapeseed than sole application of these nutrients, which demonstrates that inclusion of sulphur in rapeseed fertilization increased the efficiency of nitrogen fertilizers. Among the nitrogen and sulphur combinations tested the highest oil yield in the experiment with soil application of sulphur was obtained following application of 180 kg N·ha^{-1} and 60 kg S·ha^{-1}, and in the experiment with foliar application, following the use of 120 kg N·ha^{-1} and 20 kg S·ha^{-1}. It should be emphasized that there were generally no significant differences between the effect of 120 and 180 kg N·ha^{-1} applied together with sulphur.

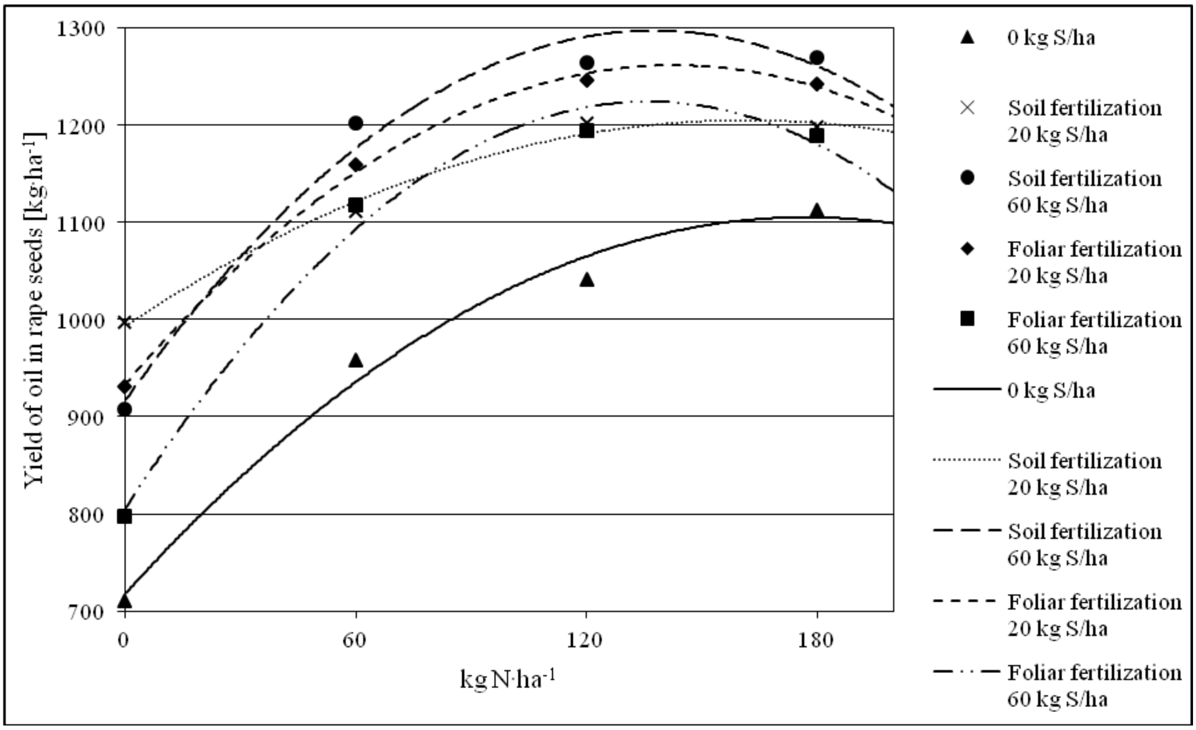


Function equations: for the dose of 0 kg S·ha^{-1}: $y = -0.0001x^2 + 0.02x + 41.9$, R = 0.96; for the dose of 20 kg S·ha^{-1} foliar application: $y = -0.0002x^2 + 0.03x + 42.4$, R = 0.96. For the remaining doses functions were not statistically significant.
Równania funkcji: dla dawki 0 kg S·ha^{-1}: $y = -0,0001x^2 + 0,02x + 41,9$, R = 0,96; dla dawki 20 kg S·ha^{-1} dolistna aplikacja: $y = -0\ 0002x^2 + 0,03x + 42,4$, R = 0,96. Dla pozostałych dawek funkcje nie były statystycznie istotne.

Figure 1. Relation between the oil content in spring rapeseed and soil and foliar fertilization with sulphur and nitrogen – means for three study years

Rysunek 1. Zależność pomiędzy zawartością tłuszczu w nasionach rzepaku jarego a doglebowym i dolistnym nawożeniem siarką oraz azotem – średnie z trzech lat badań

Regression analysis (Figure 1) indicates that without sulphur application the highest oil content can be obtained with a level of nitrogen close to 100 kg·ha^{-1}, and in the case of foliar application of 20 kg S·ha^{-1}, with 105 kg N·ha^{-1}. Furthermore, the highest yield of oil without sulphur fertilization was obtained with a level of nitrogen to 177 kg N·ha^{-1}, whereas after in-soil and foliar application of 20 and 60 kg S·ha^{-1} – with a level between 136 and 162 kg N·ha^{-1} (Figure 2).



Function equations: for the dose of 0 kg S·ha^{-1}: $y = -0.0124x^2 + 4.378x + 717.7$, $R^2 = 0.99$; for the dose of 20 kg S·ha^{-1} foliar application: $y = -0.0161x^2 + 4.6x + 993.5$, $R^2 = 0.99$; for the dose of 60 kg S·ha^{-1} foliar application: $y = -0.0226x^2 + 2.62x + 993.5$, $R^2 = 0.99$; for the dose of 20 kg S·ha^{-1} in-soil application: $y = -0.0081x^2 + 4.6x + 993.5$, $R^2 = 0.99$; for the dose of 60 kg S·ha^{-1} in-soil application: $y =-0.0201x^2 + 5.54x + 916.8$, $R^2 = 0.99$.
Równania funkcji: dla dawki 0 kg S·ha^{-1}: $y = -0,0124x^2 + 4,378x + 717,7$, $R^2 = 0,99$; dla dawki 20 kg S·ha^{-1} dolistnie aplikowanej: $y = -0,0161x^2 + 4,6x + 993,5$, $R^2 = 0,99$; dla dawki 60 kg S·ha^{-1} dolistnie aplikowanej: $y = -0,0226x^2 + 2,62x + 993,5$ $R^2 = 0,99$; dla dawki 20 kg S·ha^{-1} doglebowo aplikowanej: $y = -0,0081x^2 + 4,6x + 993,5$, $R^2 = 0,99$; dla dawki 60 kg S·ha^{-1}doglebowo aplikowanej: $y =-0,0201x^2 + 5,54x + 916,8$, $R^2 = 0,99$.

Figure 2. Relation between the oil yield of spring rapeseed and in soil and foliar fertilization with sulphur and nitrogen – means for three study years

Rysunek 2. Zależność pomiędzy wydajnością tłuszczu z nasion rzepaku jarego a doglebowym i dolistnym nawożeniem siarką oraz azotem – średnie z trzech lat badań

Many authors report a strong interaction between the level of nitrogen and sulphur on the oil yield of oilseed plants (Jamal et al., 2006; Tomar and Singh, 2007; Rudko, 2011; Varényiová et al., 2017). Fismes et al. (2000) state that the interaction of nitrogen and sulphur is synergistic if the proportion of the two nutrients in the soil is optimal for a given species, but antagonistic if one of them is present in excess. For rapeseed the optimal N:S ratio is considered to be 5-6:1 (Wielebski, 2015).

The efficiency of sulphur fertilization in plants of the *Brassicaceae* family is linked to nitrogen metabolism, because the most important functions of sulphur in the plant result from the presence of this nutrient in sulphur-containing amino acids (methionine, cysteine and cystine), which play a key role in the formation of the secondary and tertiary structure of proteins. Over 90% of the total sulphur accumulated in plants is estimated to be in the form of sulphur amino acids (Messick, 2013). Sulphur-containing amino acids are built into protein structures and are also precursors of other important compounds, such as vitamins B_1 (thiamine) and H (biotin). They are also involved in the formation of compounds with redox properties (glutathione and ferredoxin) and the active centre of numerous enzymes (De Kok et al., 2003; Ray et al., 2015).

The study demonstrated that inclusion of sulphur in fertilization of spring rapeseed, particularly in conditions of intensive nitrogen fertilization, increased the content and yield of oil, which are the most important indicators of the quality of this species.

Conclusion

Soil application of sulphur made it possible to obtain somewhat higher oil content and yield from spring rapeseeds than foliar application of this element. In each growing season higher content and yield of oil was obtained in the seeds of plants fertilized with nitrogen alone than in the plants that were not fertilized with this nutrient. In the case of oil content, only in one year of the study was N application at a rate of 120 kg $N \cdot ha^{-1}$ had a statistically more beneficial effect than 60 and 180 kg $N \cdot ha^{-1}$; in the other years there were no statistical differences between application rates. A dose of 180 kg $N \cdot ha^{-1}$ was significantly the most beneficial for the oil yield. Sole application of sulphur caused a significant increase in oil content and yield from the spring rapeseeds as compared to the control. For both criteria, in conditions of soil application of sulphur no significant differences were noted between the effect of 20 and 60 kg $S \cdot ha^{-1}$, while in the case of foliar application it was found that a dose 20 kg $S \cdot ha^{-1}$ turned out to be more efficient. Irrespective of the means of sulphur application, its use in combination with nitrogen generally resulted in higher oil content and yield of oil than when these nutrients were used separately. However, their interaction was not statistically confirmed.

Sulphur applied with or without nitrogen had a favourable effect on the oil content and yield from the spring rapeseed, which substantiates the need to include sulphur in the agrotechnical procedures for this species.

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