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Mineral composition of winter oilseed rape (*Brassica napus* L.) seeds as a tool for oil yield prognosis

Skład mineralny nasion rzepaku ozimego (*Brassica napus* L.), jako narzędzie prognozy plonu oleju

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Abstract

The key objective of winter oilseed rape cultivation, resulting from its broad spectrum of uses, is to harvest maximum yield of oil. It has been formulated a hypothesis, which assumed that mineral composition of seeds allows a reliable prediction of both crude oil concentration (COC), and yield of oil (YOI). This concept has been validated in three 2007/08, 2008/09, 2009/10 seasons. The field experimental design was composed of six fertilizing treatments: absolute control (AC), NP, NPK, NPKMgS1 (1/3 total MgS rate applied in spring), NPKMgS2, (total MgS rate applied in autumn), NPKMgS3 (2/3 - autumn, 1/3 - spring). The COC depended on both factors, but any interactional effect was found. The YOI was a result of interaction of both factors, reaching the highest value of 2.6 t*ha^{-1} in 2008 in the plot fertilized with NPKMgS2. The COC was a result of positive impact of calcium and negative by both nitrogen, and magnesium. The YOI was the best predicted by calcium concentration. It has been found that any calcium concentration increase above 3.0 g*kg^{-1} DM resulted in decrease of the crude oil yield. The prediction of both oil characteristics was more reliable based on nutrient accumulation in seeds. As again magnesium was the key predictor of COC, exerting a negative impact on this characteristic. The optimum set of YOI predictors was depended on the group of treatments. In all considered treatments, the YOI was affected by the interactional effect of phosphorus (negative), and potassium (positive). In the set of treatments, composed of NPK and its variants with MgS rates, the YOI was depended on the amount nitrogen and zinc in seeds. The first nutrient affected positively and the second negatively the yield of crude oil.

Keywords: balanced fertilization, magnesium sulfate, nutrient accumulation, nutrient concentration

Streszczenie

Głównym celem uprawy rzepaku ozimego, wynikającym z jego szerokiego spektrum zastosowań, jest maksymalizacja plonu oleju. Sformułowano hipotezę, która zakłada, że skład mineralny nasion rzepaku umożliwia predykcję zarówno koncentracji, jak i plonu oleju surowego. Koncepcję tą walidowano w latach 2007/08, 2008/09, 2009/10. Układ doświadczalny składał się z sześciu wariantów nawozowych: kontrola absolutna (AC), NP, NPK, NPKMgS1 (1/3 ogólnej dawki MgS - stosowana wiosną), NPKMgS2, (całkowita dawka MgS - stosowana jesienią), NPKMgS3 (2/3 - jesień, 1/3 - wiosna). Koncentracja oleju surowego zależała od obu czynników, lecz nie stwierdzono między nimi współdziałania. Plon oleju surowego był wynikiem współdziałania obu czynników, osiągając największa wartość w wariancie NPKMgS2, wynoszącą 2.6 t*ha^{-1} w roku 2008. Koncentracja oleju surowego w nasionach była wynikiem pozytywnego wpływu wapnia oraz negatywnego azotu i magnezu. Jednakże jakikolwiek wzrost koncentracji wapnia w nasionach powyżej 3.0 g*kg^{-1} s.m. prowadził do spadku plonu oleju. Akumulacja składników pokarmowych w nasionach była dużo silniejszym niż koncentracja predykatorem obu cech oleju. Magnez okazał się ponownie głównym wskaźnikiem zawartości oleju w nasionach, wywierając ujemny wpływ na tą cechę. Optymalny zestaw predykatorów plonu oleju był różny, zależnie od grupy kombinacji nawozowych. Ujmując wszystkie badane kombinacje plon oleju zależał od współdziałania fosforu (ujemny) i potasu (dodatni). W grupie składającej się z NPK i wariantów z dawkami MgS zależał natomiast od ilości azotu i cynku w nasionach. Pierwszy ze składników kształtował dodatnio a drugi ujemnie plon oleju.

Słowa kluczowe: akumulacja, nawożenie zbilansowane, siarczan magnezu, zawartość składników mineralnych

Streszczenie szczegółowe

Głównym celem uprawy rzepaku ozimego, wynikającym z szerokiego spektrum zastosowań, obejmujących zarówno produkcję olejów roślinnych a współcześnie także biopaliwa, jest maksymalizacja plonu oleju. Sformułowana hipoteza badawcza zakładała, że skład mineralny nasion rzepaku warunkuje zarówno zawartość, jak i plon oleju, a tym samym umożliwia wiarygodne oszacowanie obu cech rzepaku ozimego. Koncepcję tą walidowano w latach 2007/08, 2008/09, 2009/10 w doświadczeniu składającym się z sześciu wariantów nawozowych: kontrola absolutna (AC), NP, NPK, NPKMgS1 (1/3 ogólnej dawki MgS - stosowana wiosną), NPKMgS2, (całkowita dawka MgS - stosowana jesienią), NPKMgS3 (2/3 - jesień, 1/3 - wiosna). Warianty te podzielono na dwie grupy: i) pierwszą, obejmującą wszystkie warianty, określono, jako niezbilansowany system nawożenia (IBFS), a ii) drugą, zawierającą kombinację z NPK i wszystkie warianty z MgS, jako zbilansowany system nawożenia (BFS). Koncentracja oleju surowego zależała od obu czynników nawozowych, jak i warunków pogodowych w kolejnych latach badań, lecz nie stwierdzono między nimi współdziałania. Plon oleju surowego był wynikiem współdziałania obu czynników, osiągając największa wartość w wariancie NPKMgS2, wynoszącą 2.6 t*ha^{-1} w roku 2008. W kolejnym roku (2009) uzyskano plony mniejsze, a największy, 2.25 t*ha^{-1} odnotowano w wariancie z NPK. W roku 2010 plony oleju były najmniejsze, a największy, wynoszący 1.6 t*ha^{-1} uzyskano w wariancie z MgS2. Koncentracja składników mineralnych w nasionach poza azotem, potasem i manganem, wykazała zmienność warunkowaną przebiegiem pogody. Wahania zawartości składników były duże, lecz poza azotem, fosforem i manganem, mieściły się w zakresach podawanych, jako standardowe. Akumulacja składników wykazała dużo większą zmienność, w tym zależała od systemu nawożenia, podczas gdy czynnik pogodowy nie różnicował ilości wapnia i miedzi. Współdziałanie obu czynników odnotowano dla azotu i manganu. W grupie IBFS koncentracja oleju surowego zależała od współdziałania azotu i wapnia. Pierwszy z pierwiastków wywierał ujemny, a drugi dodatni wpływ na analizowaną cechę. W grupie BFS wartość tej cechy kształtowało dodatnie działanie fosforu oraz ujemne magnezu. Przeprowadzone badania wykazały, że obu grupach kombinacji nawozowych, wzrost koncentracji wapnia w nasionach powyżej 3.0 g*kg^{-1} s.m., prowadził do spadku plonu oleju. Głównym antagonistą wapnia w kształtowaniu plonu oleju był magnez. Akumulacja składników pokarmowych w nasionach okazała się bardziej wiarygodnym, jak wynika z wartości R^2, predykatorem obu cech oleju. Wzrost akumulacji fosforu i cynku w nasionach z grupy IBFS prowadził do spadku zawartości oleju. Natomiast w grupie BFS czynnikiem definiującym, lecz ujemnie wartość tej cechy, okazał się magnez. Optymalny zestaw predykatorów plonu oleju był różny, zależnie od grupy kombinacji. W grupie IBFS zależał od współdziałania fosforu (ujemny) i potasu (dodatni), podczas gdy w grupie BFS wynikał z synergistycznego współdziałania azotu, wykazującego wpływ dodatni i cynku, przejawiającego działanie ujemne na plon oleju.

W konkluzji końcowej można stwierdzić, że współdziałanie wapnia, azotu, magnezu i cynku okazało się kluczowe dla maksymalizacji plon oleju surowego. Istotną rolę odgrywał magnez, który jako naturalny antagonista wapnia, zwłaszcza w warunkach stresu, sprzyjającego akumulacji tego właśnie składnika w nasionach. Zastosowanie magnezu, przeciwdziałając akumulacji wapnia w nasionach, jest, więc zabiegiem istotnie zwiększającym prawdopodobieństwo wyprodukowania większego plonu oleju przez rzepak.

Introduction

The importance of oilseed rape has increased tremendously in the last two decades. There are numerous reasons for the observed progress. The key attribute of modern varieties is both a high-yielding potential and quality of vegetable oil, fulfilling food requirements (Abbadi and Leckband, 2011). On the other hand, this crop has become lately an important source of renewable energy. It results from technical progress, creating new areas for oilseed rape utilization (Milazzo et al., 2013; Kazamia and Smith, 2014). The main product of winter oilseed rape, oil, constituting 18% of principal energy yield, is a good source for biodiesel production. The oil cake (22%) and straw (60%) can be used for heat and electricity generation (Jankowski et al., 2015). The increasing, but competitive demands for vegetative oil require a permanent progress in oil crop production (Pin Koh and Ghauzul, 2008). However, the yield progress is mainly due to the harvested area than yield gain (Rondanini et al., 2012). The increase in the global area under oilseed rape, within the period 2004-

2013, was from 25.3 to 36.4 mln ha. At the same time, seed yield progress was lower, increasing from 1.838 to 1.994 t*ha^{-1} (FAOSTAT, 2015). The detailed analysis of yield progress during this decade is highly confusing. The global yield gain during this frame time was positive, but amounted only to 18.5 kg*ha^{-1}*yr^{-1}. Among the leaders, the significant annual yield gain took place in China and Canada, amounting to 48 and 9.4 kg*ha^{-1}*yr^{-1}, respectively. The yield potential of winter oilseed rape is calculated at the level of 3.6 t*ha^{-1} for The Czech Republic, 3.3 for Hungary, 3.7 for Poland, and 3.5 for Romania (Supit et al., 2010). The existing yield gap is substantial, but country specific. Real yields in these countries harvested during the period 2008-2013 are much lower, amounted to 3.0 ±0.26, 2.4 ±0.26, 2.7 ±0.33, and 1.8 ±0.34 t*ha^{-1}, respectively (FAOSTAT, 2015). The key reason for the existing yield gap and its year-to-year variability is the imbalanced use of basic nutrients, like N, P, K. Nutrient management in all these countries, irrespective on the soil fertility level, is nitrogen oriented. This strategy leads to significant mining of soil nutrients (Grzebisz et al., 2010a). There is a deep gap in knowledge, concerning the chemical composition of oilseed rape seeds with respect to crude oil content and yield. In fact, most published papers focus only on nitrogen, indicating its negative impact on the crude oil content (COC). The effect of nitrogen rates on yield of oil (YOI) is highly unpredictable, following the linear or quadrate regression model (Rathke et al., 2005). There is almost no current knowledge concerning concentration of other nutrients in seeds and their relationships with oil concentration and oil production by oilseed rape.

The minor objective of this paper is to indicate to how the extent a balanced fertilization of oil seed rape affects both crude oil content and its yield. The major objective is to predict both, crude oil concentration and yield of oil, based on mineral composition of oilseed rape seeds.

Materials and methods

Description of site and general growing condition

Studies on winter oilseed rape seed mineral status were carried out during three consecutive seasons 2007/08, 2008/09, and 2009/10 at Donatowo (52°04’N; 16°51’E), Poland. Weather conditions were favorable for plant growth in 2008 and 2009. In 2010 excessive rainfalls in autumn resulted in the plant density drop below 30 m^{-2}. It was the key reason for disturbance in yield formation, and consequently, in lower yield of seeds (Szczepaniak, 2014). The field experiment was established on a soil originated from loamy sand underlined by sandy loam, classified as Albic Luvisol. Soil fertility as indicated by agrochemical characteristics was satisfactory for producing high yield of seeds (in the topsoil pH 6.0-6.6; P and K determined by Egner-Riehm method 69-90 and 103-162 mg*kg^{-1} and Mg by Schachtschabel metod 5.2-7.0 mg*kg^{-1}). The study basis on the one factorial trial, consisting of six treatments, replicated four times: absolute control (AC), NP, NPK, NPKMgS1 (1/3 total MgS rate, spring applied), NPKMgS2, (total rate, autumn = 16.3 kg Mg*ha^{-1} and 18 kg S*ha^{-1}), NPKMgS3 (2/3 - autumn, 1/3 - spring). The variety Chagall was sown at the rate of 3.0 kg*ha^{-1} seeds in the last decade of August. At maturity, plants were harvested from the area of 15 m^2 by a plot combine harvester. Phosphorus (di-ammonium phosphate, 18% N, 46% P_2O_5) was applied just prior sowing in the rate of 30.1 kg P*ha^{-1}. Potassium (muriate of potash (60% K_2O) and/or Korn-Kali (40% K_2O, 6%MgO, 4%Na_2O, 12%SO_3) was applied prior sowing in the rate of 149.4 kg K*ha^{-1}. Magnesium and sulfur were applied as Korn-Kali and/or Epsom Salt in accordance with the treatment schedule. Plants were dressed with nitrogen (ammonium nitrate, 34% N) at the rate of 27 kg N*ha^{-1} before sowing, 102 kg N*ha^{-1} before spring’s regrowth (BBCH 21) and 78 kg*ha^{-1} at BBCH 30.

Data colection

The concentration of crude fat in seeds was determined by light petroleum ether extraction on a Soxlet apparatus. Nitrogen concentration in seeds was determined by a standard macro-Kjeldahl procedure. Seeds for other nutrient's determination were first ignited at 600 °C, and then dissolved in 33% HNO_3. Phosphorus concentration was analyzed by the vanadium-molybdenum method and measured with the Specord 40 at 436 nm wave; potassium and calcium by the flame-photometry; magnesium, and micronutrients by atomic-absorption spectrometry - flame type. All results are expressed on the dry matter (DM) basis. The amount of nutrient accumulations in seeds were calculated by multiplication of its concentration, and seed dried mass.

Statistical analysis

The obtained data were subjected to the analysis of variance (STATISTICA 10). The differences between treatments were evaluated with the Tukey’s test. In tables, figures, and equations, results from the F test (***, **, * indicate significance at the P<0.1%, 1%, and 5%, respectively) are given. The developed regression models rely on the computing procedure, in which a consecutive variable was removed from the multiple linear regressions in the step-by-step manner. The key criterion for the chosen model was the highest F-value and significance of all independent variables (Konys and Wisniewski 1984).

Results and Discussion

Crude oil content and yield

Crude oil content (COC) was significantly affected by year and fertilizing treatments (Figure 1). However, any interrelationship between these two factors took place. The impact of years was specific, resulting in significantly higher COC in 2010 compared to other two years. The key reason was lower plant density in this particular year (Szczepaniak, 2014). The applied fertilizers, irrespectively on composition, resulted in COC decrease compared to the untreated control. The increasing rate of MgS fertilizer resulted in gentle COC decrease. This is the only trend, mostly addressed to nitrogen (Barłóg and Grzebisz, 2004; Rathke, 2005). Data concerning magnesium impact on oil content in the *Brassica* species are controversial (Gerendás and Führs, 2013).

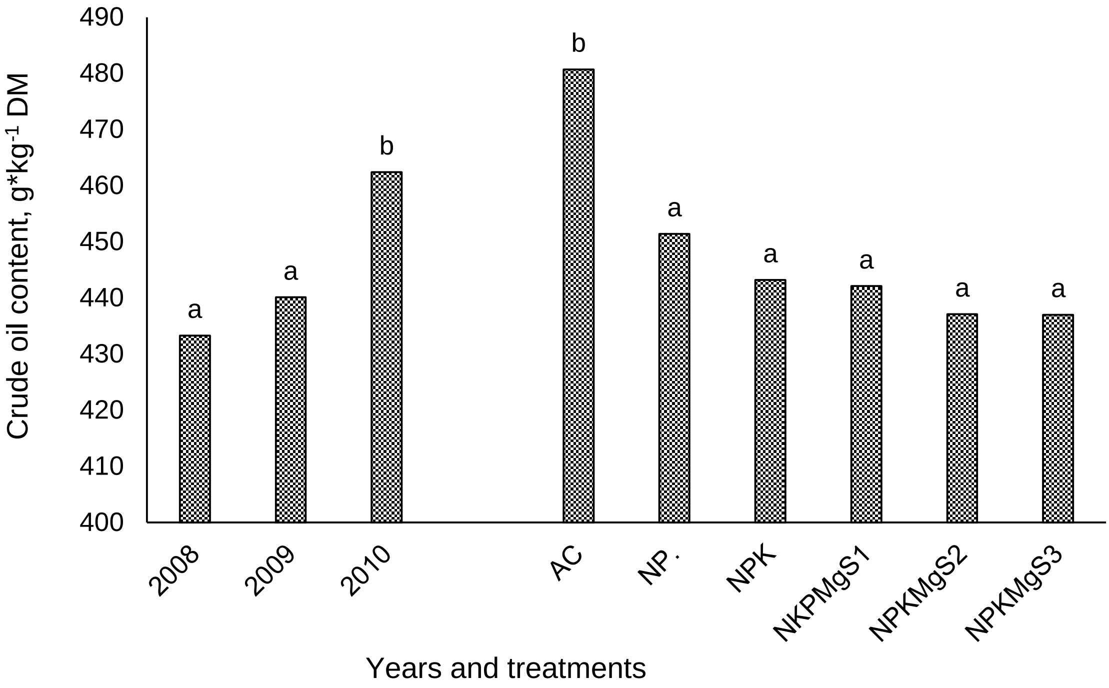

Figure 1. Effect of years and fertilizing treatments on crude oil content (COC); [a] the same letter means a lack of significant differences at $P<0.05$.

Rycina 1. Wpływ lat badań i wariantów nawożenia na zawartość tłuszczu surowego (COC); [a] warianty oznaczone tą samą literą nie różnią się istotnie dla $P<0.05$.

The yield of crude oil (YOI) showed a strong year-to-year variability. It decreased, averaged over fertilizing treatments, in the order: 2008>2009>2010. The impact of fertilizing treatments was a year dependent. In 2008, the highest YOI was harvested in the treatment with magnesium sulfate applied in the full rate in autumn (MgS2). A slightly lower yield was harvested in the treatment with split application of magnesium sulfate (MgS3). In 2009, the highest yield was an attribute of the NPK treatment. In the third year, 2010, in general yields were much lower in respective treatments compared to both previous years. The highest yields, harvested in magnesium treatments, were at the level of the absolute control in 2008 (Figure 2).

In this study, the key factor controlling the YOI (in $t*ha^{-1}$) was the total seed yield (TSY), and next COC (for details see Szczepaniak, 2014):

$YOI = 0.4*TSY + 0.202$ for $n = 18$, $R^2 = 0.89$, and $P<0.001$.

$YOI = -0.0127*COC + 7.5$ for $n = 18$, $R^2 = 0.44$, and $P<0.01$.

This set of equations implicitly underlined the hypothesis, concerning the dominant role of the seed yield as the YOI determinant. Therefore, any factor affecting positively seed yield is important for the YOI prediction. On the other hand, any factor increasing seed yield impacted negatively COC. The applied magnesium fertilizer, irrespective of environmental conditions, resulted in COC decrease. In spite of this, the harvested YOI responded positively to magnesium fertilizers. This study confirms the hypothesis by Grzebisz et al. (2010b) and Grzebisz (2013), concerning a supporting effect of applied magnesium on plant growth under conditions of a mild stress. This situation occurred just in 2008.

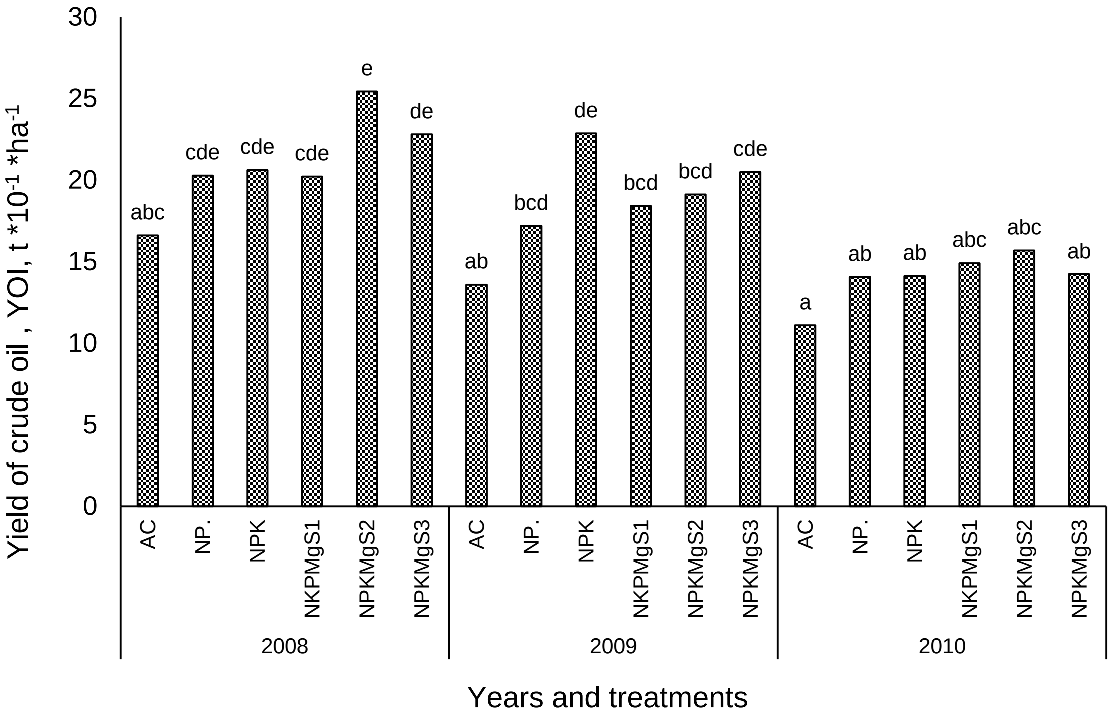

Figure 2. Yield of crude oil (YOI) as a result of fertilizing treatments effect on the background of years; ^{a} the same letter means a lack of significant differences at P<0.05.

Rycina 2. Wpływ wariantów nawożenia na plon tłuszczu surowego (YOI) na tle lat badań; ^{a} warianty oznaczone tą samą literą nie różnią się istotnie dla P<0.05.

Nutrient concentration in seeds

The nutrient concentration in seeds of oilseed rape showed, in general, a significant year-to-year variability. The impact of applied fertilizers was observed only to nitrogen, potassium and manganese. It is necessary to point out the fact that there has not been found any interrelationship between both factors was found (Table 1).

Nitrogen concentration in seeds in consecutive years was inversely correlated with oil yield. The impact of fertilizing treatments on nitrogen content was significant. The lowest value was determined in seeds of the absolute control and the highest in seeds of plants fertilized with NPK and MgS applied only in spring. As reported by Rathke et al. (2005), the yield of oil increased progressively with nitrogen concentration in seeds up to 35 g*kg^{-1} DM. In our study this level of N concentration was an attribute of all treatments fertilized with fertilizer nitrogen (Table 1).

Table 1. Nutrient concentration in seeds of oilseed rape

Tabela 1. Zawartość składników pokarmowych w nasionach rzepaku ozimego

Factor and factor level	N	P	K	Ca	Mg	Zn	Mn	Cu
	g*kg^{-1} DM					mg*kg^{-1} DM		
Fertilizing treatments								
AC	30.0^{a}	8.50	8.21^{a}	3.84	2.70	44.0	34.2	3.90
NP	34.9^{ab}	8.75	8.59^{ab}	4.06	2.86	47.6	39.6	4.48
NPK	35.9^{b}	9.25	9.24^{b}	3.85	2.77	47.0	38.9	4.09
NPKMgS1	35.6^{b}	8.65	8.84^{ab}	4.06	2.90	50.8	40.8	4.30
NPKMgS2	35.2^{ab}	9.13	9.04^{ab}	3.83	2.75	41.9	38.3	4.08
NPKMgS3	34.9^{ab}	9.12	9.19^{b}	3.95	2.77	47.1	39.8	4.29
Years								
2008	30.0^{a}	8.00^{b}	8.96^{ab}	3.06	2.82	30.6	30.3	3.26
2009	35.9^{b}	5.88^{a}	8.08^{a}	3.66	3.01	67.7	50.7	3.97
2010	37.3^{c}	12.82^{c}	9.52^{b}	5.08	2.54	40.8	34.8	5.34
Source of variation								
Year	***	***	***	***	***	***	***	***
Fertilizing	***	n.s.	**	n.s.	n.s.	n.s.	**	n.s.
Year x fertilizing	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

***, **, * significant at P<0.001, P<0.01 and P<0.05, respectively; n.s. – not significant; ^{a} the same letter means a lack of significant differences at P<0.05.

*, **, *** istotne odpowiednio na poziomie P<0.001; P<0.01 and P<0.05; n.s. – nie istotne; ^{a} warianty oznaczone tą samą literą nie różnią się istotnie dla P<0.05.

Phosphorus concentration in seeds showed a quite different pattern in response to environmental conditions. The lowest concentration was documented in 2009 and the highest in 2010. Phosphorus concentration in 2009 was 2-times lower compared to 2010. However, the YOI was as 1:0.75. As reported by Barłóg et al. (2005), phosphorus concentration in seeds at the level of 7 g P*kg^{-1} DM is typical for high yielding crops. The observed dilution effect in 2009 indicates an elevated efficiency of this nutrient, irrespectively on soil P supply. The reverse situation took place in 2010, when phosphorus was not used as efficiently as in 2009 and 2008. The very similar trend was an attribute of potassium, but the differences between 2009 and 2010 were much lower. Potassium concentration reached the lowest value in the absolute control and the highest in seeds of plants fertilized with NPK or fertilized with NPKMgS3. There was found that seed calcium concentration decreased with increasing yield of crude oil. Concentration of both nutrients was in the standard range (Barłóg et al., 2005). A quite different pattern was an attribute of magnesium. Its concentration increased in the order: 2009>2008>2010. The documented concentration was slightly below the range reported by Barłóg et al. (2005). The same pattern was observed for copper. For zinc and manganese, the order of years was as follows: 2009>2010>2008. The values noted in 2009 were almost twice as high compared to 2008, a year with the highest yield of oil. Data presented by Barłóg et al. (2005) for micronutrients are in the range documented in 2008.

The analysis of relationships between respective pairs of nutrients was conducted in two groups of treatments (Table 2). The first one, termed as the Imbalanced Fertilizing System (IBFS), represents all studied treatments, including the unfertilized control. The second one, termed as the Balanced Fertilizing System, contains NPK and all NPK + MgS treatments. As results from Table 2, the relationships between consecutive pairs of nutrients were highly stable, as indicated by values of correlation coefficients. As a rule, they were slightly higher in the BFS group. A significant increase was noted for two pairs: K x Mg, and K x Mn. Their negative signs underline the antagonism exerted by potassium on magnesium and manganese concentration. The second objective of the applied analyzing procedure was to define the best set of nutrients predicting COC and/or YOI. Magnesium was the only nutrient significantly affecting COC in the IBFS. However, its predictive worth as results from the R^2 value was low (0.36). The applied stepwise analysis showed the quite different set of COC indicators. The highest COC was achieved, as shown in Figure 3, provided the decrease in N and simultaneous increase in calcium concentration. This interaction was also low, explaining only 46% of COC variability. In the BFS, the significant correlations with COC were noted for P, and Mg. The first element exerted positive and the second negative impact on this characteristic. The stepwise regression implicitly indicated on magnesium as the decisive nutrient for COC prediction:

$COC = -4169*Mg + 556.4$ for $n = 12$, and $R^2 = 0.51$, and $P<0.05$.

The yield of crude oil was much stronger dependent compared to COC on nutrient concentration in seeds. Significant relationships were found between phosphorus, magnesium, copper and the YOI in the IBFS and between nitrogen, phosphorus, and copper and YOI in the BFS (Table 2). In spite of this, calcium concentration was the decisive element for YOI prediction. As results from the developed quadrate regression models, any increase of calcium concentration above 3.0 $g*kg^{-1}$ DM led to YOI decrease (Figure 4). The minimum yield of 1.4 $t*ha^{-1}$ was related to calcium concentration of 5.3 $g*kg^{-1}$ DM in the IBFS and of 5.7 g $Ca*kg^{-1}$ DM in the BFS. The key question is to recognize a nutrient working in the opposite manner to calcium. Among four elements, showing a significant correlation with calcium, an antagonistic relation was documented only for magnesium. This nutrient, in spite of negative impact on COC was positively correlated with YOI. The key reason was its positive effect on seed yield (Szczepaniak et al., 2015).

Table 2. Matrix of correlation for nutrient concentration in oilseed rape seeds and yield of oil (YOI): a) all treatments, IBFS; b) balanced treatments, BFS

Tabela 2. Współczynniki korelacji między zawartością składników pokarmowych w nasionach rzepaku a plonem tłuszczu surowego (YOI): a) wszystkie warianty, IBFS; b) warianty zbilansowane, BFS

Elements	P	K	Ca	Mg	Zn	Mn	Cu	YOI
a) all treatments, IBFS, n=18								
N	0.34	0.25	0.69**	-0.08	0.50*	0.53*	0.71**	-0.28
P		0.79***	0.78***	-0.85***	-0.50*	-0.53*	0.73**	-0.59*
K			0.42	-0.59*	-0.51*	-0.50*	0.36	-0.16
Ca				-0.54*	0.08	0.01	0.98***	-0.76***
Mg					0.61**	0.66**	-0.47*	0.48*
Zn						0.97***	0.12	-0.07
Mn							0.09	0.07
Cu								-0.68**
b) balanced treatments, BFS, n=12								
N	0.34	0.03	0.75^{**}	-0.23	0.61^{*}	0.49	0.76^{**}	-0.69^{*}
P		0.86***	0.81**	-0.89***	-0.51	-0.61*	0.75**	-0.76**
K			0.48	-0.72**	-0.65*	-0.72**	0.39	-0.50
Ca				-0.66*	0.01	-0.13	0.98**	-0.91***
Mg					0.55	0.62*	-0.62*	0.52
Zn						0.97***	0.06	-0.04
Mn							-0.06	0.07
Cu								-0.86***

***, **, * significant at P<0.001, P<0.01 and P<0.05, respectively

*, **, *** istotne odpowiednio na poziomie P<0.001; P<0.01 oraz P<0.05

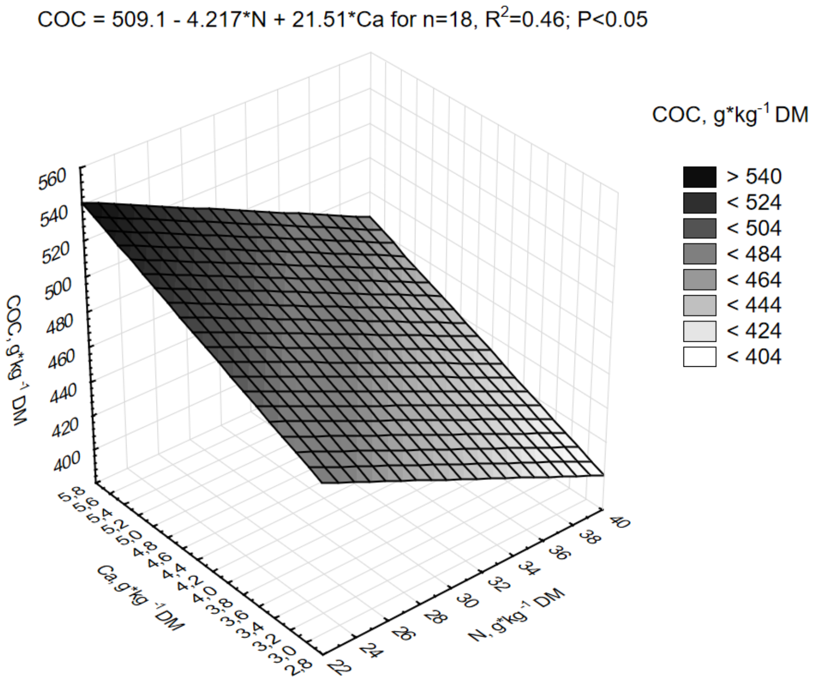

Figure 3. Crude oil content (COC) as affected by N and Ca concentration in seeds

Rycina 3. Zawartość tłuszczu surowego jako funkcja zawartości w nasionach N i Ca

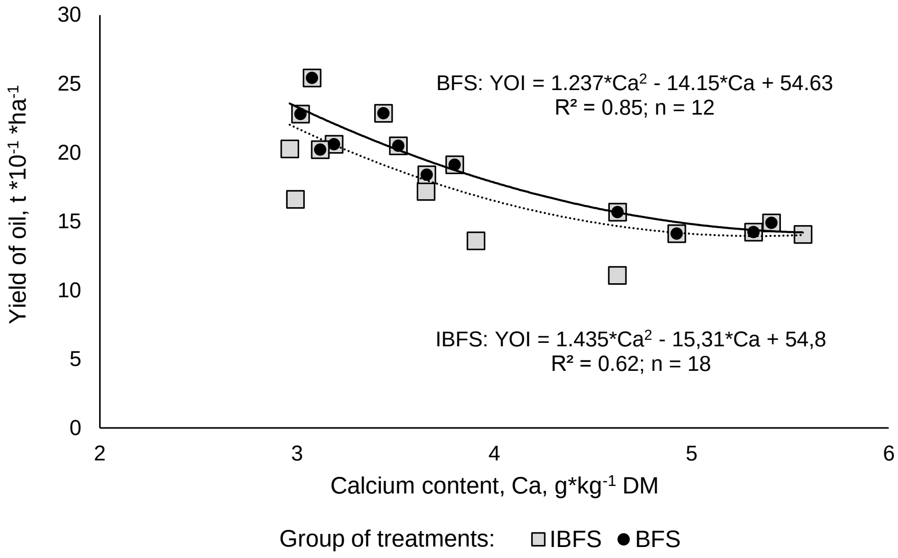

Figure 4. Calcium content in seeds and the yield of crude oil (YOI). Legend: IBFS – Imbalanced Fertilizing System , represents all studied treatments, including the unfertilized control; BFS – Balanced Fertilizing System, contains NPK and all NPK+MgS treatments.

Rycina 4. Plon tłuszczu surowego (YOI) jako funkcja zawartości Ca w nasionach. Legenda: IBFS – niezbilansowane systemy nawożenia; BFS – zbilansowane systemy nawożenia, zawierające NPK i wszystkie NPK+MgS warianty.

Nutrient accumulation in seeds

The quantities of nutrients in seeds at harvest were much more than their concentration sensitive to experimental factors (Table 3).

Table 3. Nutrient accumulation in seeds of winter oilseed rape

Tabela 3. Akumulacja składników pokarmowych w nasionach rzepaku ozimego

Factor and factor level	N	P	K	Ca	Mg	Zn	Mn	Cu
	kg*ha^{-1}					g*ha^{-1}		
Fertilizing treatments								
AC	84.3^{a}	23.4^{a}	23.5^{a}	10.6^{a}	7.8^{a}	126.2^{a}	97.8^{a}	11.0^{a}
NP	131.6^{b}	32.0^{b}	32.5^{b}	14.8^{b}	11.0^{b}	178.3^{ab}	148.4^{b}	16.4^{b}
NPK	154.4^{bc}	37.4^{bc}	39.3^{bc}	16.1^{b}	12.2^{b}	206.5^{b}	171.5^{b}	17.3^{b}
NPKMgS1	144.5^{bc}	34.1^{bc}	36.1^{bc}	16.0^{b}	12.0^{b}	208.7^{b}	168.0^{b}	16.9^{b}
NPKMgS2	158.7^{c}	39.8^{c}	41.2^{c}	17.0^{b}	12.6^{b}	188.7^{b}	171.9^{b}	18.0^{b}
NPKMgS3	151.7^{bc}	37.4^{bc}	39.8^{bc}	16.4^{b}	12.4^{b}	208.9^{b}	178.8^{b}	17.8^{b}
Years								
2008	144.4^{ab}	38.1^{b}	42.8^{c}	14.5	13.4^{b}	146.5^{a}	144.8^{b}	15.5
2009	154.2^{b}	25.0^{a}	34.4^{b}	15.4	12.8^{b}	287.4^{b}	216.9^{c}	16.9
2010	113.9^{a}	39.0^{b}	29.1^{a}	15.5	7.8^{a}	124.7^{a}	106.5^{a}	16.4
Source of variation								
Year	***	***	***	n.s.	***	***	***	n.s.
Fertilizing	***	***	***	***	***	**	***	***
Year x fertilizing	*	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.

***, **, * significant at $P<0.001$, $P<0.01$ and $P<0.05$, respectively; n.s. – not significant; ^{a} the same letter means a lack of significant differences at $P<0.05$.

*, **, *** istotne odpowiednio na poziomie $P<0.001$; $P<0.01$ and $P<0.05$; n.s. – nie istotne; ^{a} warianty oznaczone tą samą literą nie różnią się istotnie dla $P<0.05$.

Two of eight elements such as calcium and copper did not show any year-to-year variability. Two of eight elements, i.e. nitrogen and manganese responded significantly to interaction of years and fertilizing treatments.

The amount of nitrogen in seeds increased in the order: 2010<2008<2009. A very similar pattern was observed for zinc, and manganese. The impact of years on phosphorus was quite specific. The highest accumulation was recorded in 2008 and 2010, years with contrastive yields of crude oil. The quantity of potassium and magnesium accumulated in seeds followed the order recorded for yield of crude oil (2010<2009<2008). In the case of magnesium the year induced, differences were more striking. In 2010, magnesium quantity in seeds constituted only 58% of the value recorded in 2008. For yield of crude oil, this relation was as 1:0.64.

The effect of fertilizing treatments on nutrient accumulation in seeds was nutrient-specific. The most distinctive impact of treatments was noted for nitrogen, phosphorus and potassium. The highest amount of these nutrients was an attribute of plants fertilized with magnesium sulfate applied in the full rate in autumn (MgS2). In the case of other nutrients, their quantities were at the same level for almost all fertilizing systems, except the absolute control (Table 3).

The analysis of relationships between pairs of nutrients was both fertilizing system and nutrient specific (Table 4). The most conspicuous impact of fertilizing systems refers to the number of significant relationships in each of them. In general, except phosphorus and zinc, it decreased in the BFS group of treatments. The highest decrease from six to one was noted for copper and from five to one for calcium. The observed phenomenon stresses the advanced nutritional status in the BFS set of treatments. At the same time, the most conspicuous changes in coefficients were documented for two pairs: P x Zn, which underwent a change from 0.45 to -0.87*** and P x Mn from -0.28 to -0.81***. It simply means that any increase in P accumulation in seeds led to decrease in both micronutrient quantities.

In the IBFS set of treatments, the effect of nutrient accumulation on crude oil content was, except phosphorus, significant. In spite of this, the applied stepwise regression indicates on phosphorus as one of the most important nutrients in COC prediction. The optimal sets of nutrients were as follows:

$COC = 534.7 - 0.918*P - 2.805*Mg - 0.125*Zn$ for $R^2 = 0.68; P<0.01$

$COC = 533.7 - 1.344*P - 0.218*Zn$ for $R^2 = 0.59; P<0.01$

These two equations clearly indicate that all these nutrients affected negatively crude oil content. The highest COC was achieved provided their lowest accumulation in seeds. For phosphorus, it was at the level of 15 kg $P*ha^{-1}$ and for zinc at 60 $g*ha^{-1}$.

In the BFS set of treatments, COC depended significantly only on magnesium accumulation. This nutrient exerted a negative impact on this characteristic:

$COC = 472.8 - 2.67*Mg$ for $R^2 = 0.39$ and $P<0.05$.

The yield of crude oil was differently predicted in both fertilizing systems. In the IBFS, four nutrients were significantly correlated with YOI. Based on the stepwise regression, the best set of nutrients was limited to phosphorus and potassium (Figure 5).

Table 4. Matrix of correlation for nutrient accumulation in oilseed rape seeds and yield of oil (YOI): a) all treatments, IBFS; b) balanced treatments, BFS

Tabela 4. Współczynniki korelacji między akumulacją składników pokarmowych w nasionach rzepaku a plonem tłuszczu surowego (YOI): a) wszystkie warianty, IBFS; b) warianty zbilansowane, BFS

Elements	P	K	Ca	Mg	Zn	Mn	Cu	YOI
a) all treatments, IBFS, n=18								
N	0.22	0.83***	0.74***	0.89***	0.70**	0.85***	0.75***	0.86***
P		0.51*	0.53*	0.05	-0.45	-0.28	0.43	0.23
K			0.54*	0.87***	0.27	0.50*	0.51*	0.93***
Ca				0.44	0.42	0.52*	0.97***	0.44
Mg					0.61**	0.78***	0.47*	0.95***
Zn						0.96***	0.49*	0.44
Mn							0.59*	0.65**
Cu								0.47
b) balanced treatments, BFS, n=12								
N	-0.45	0.69*	0.37	0.92***	0.74**	0.85***	0.44	0.89***
P		0.19	-0.08	-0.40	-0.87***	-0.81**	-0.22	-0.15
K			-0.04	0.81**	0.08	0.29	-0.03	0.91***
Ca				0.08	0.34	0.28	0.92***	0.15
Mg					0.58*	0.74**	0.17	0.94***
Zn						0.96***	0.46	0.40
Mn							0.43	0.59*
Cu								0.22

***, **, * significant at P<0.001, P<0.01 and P<0.05, respectively

*, **, *** istotne odpowiednio na poziomie P<0.001; P<0.01 oraz P<0.05

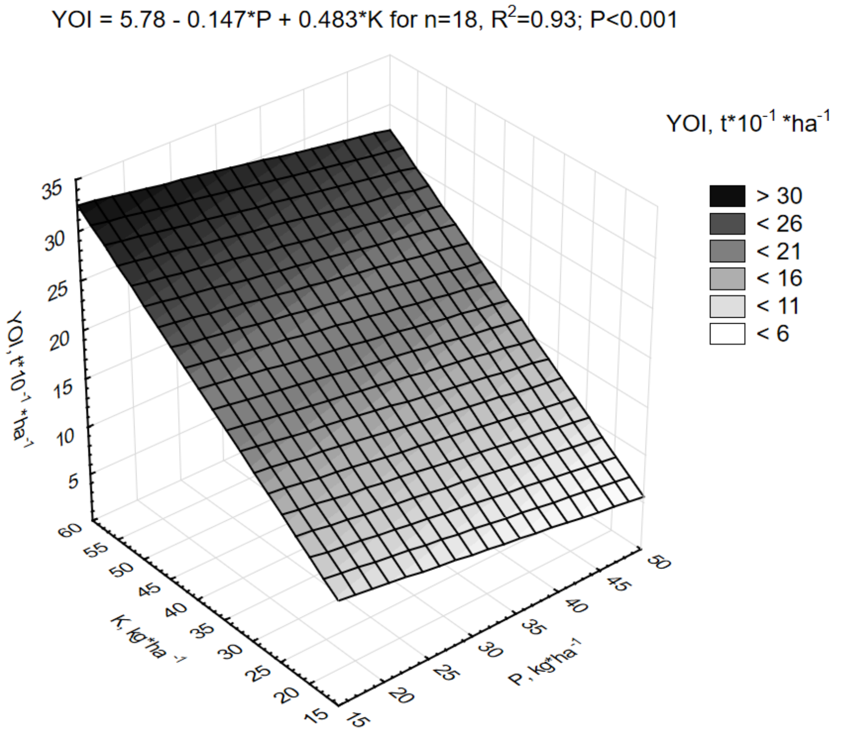

Figure 5. Crude oil yield (YOI) as affected by P and K accumulation in seeds

Rycina 5. Plon tłuszczu surowego (YOI) jak funkcja akumulacji w nasionach P i K

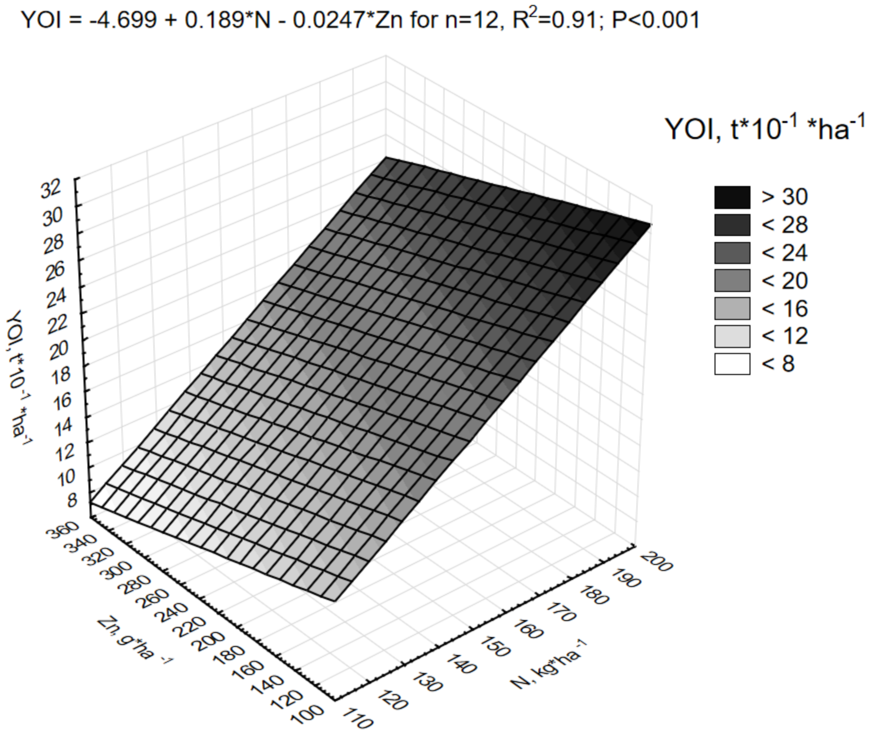

Figure 6. Crude oil yield (YOI) as affected by N and Zn accumulation in seeds

Rycina 6. Plon tłuszczu surowego (YOI) jak funkcja akumulacji w nasionach N i Zn

Their impact on the YOI was highly significant, but contradict, i.e. positive for potassium and negative for phosphorus. On the one hand, the obtained pattern of YOI underlines an importance of potassium in crude oil production by oilseed rape. This effect can be explained by the huge amount of assimilates transported to developing seeds during the seed filling period. The role of potassium in this process is well documented (White, 2013). On the other hand, the unwilling impact of phosphorus as indicating by the negative sign of the correlation coefficient is misleading. It simply informs about low phosphorus efficiency. The relatively low amount of P needed for reaching the top YOI yield indicates on its huge potential productivity, which was not exploited in the studied case. However, the decisive set of nutrients in the BFS group was quite different, compared the IBFS. The highest yield of crude oil was achieved provided the increase of nitrogen but simultaneous decrease in zinc quantities in seeds (Figure 6).

Conclusions

Magnesium sulfate revealed as the crucial compound significantly affecting oil production by winter oilseed rape. The effect of magnesium sulfate application revealed the best under conditions of mild water stress, as in 2008. It did not reveal under ample water supply, like in 2009 or under deep disturbance of yield formation, which took place in 2010. In the first case, the reason was high nitrogen concentration leading to sharp decrease in crude oil concentration. In the second case, the increasing calcium concentration in seeds led to drastic decrease of crude oil yield. It has been documented that any increase in calcium concentration above 3.0 g*kg^{-1} DM resulted in the yield of crude oil decrease. This negative effect can be partly broken by applying magnesium sulfate. The best time of magnesium sulfate application, as results from the study, is autumn. The prediction of oil concentration and its yield was more reliable based on nutrient accumulation than its concentration in seeds. The optimum set of oil yield predictors depended on the supposed nutrient balance in the oilseed rape crop. The study implicitly showed that in the set of plots composed of differently fertilized crops, the prediction of yield of oil depended on basic nutrients, like phosphorus and potassium. In the well nitrogen balanced set of treatments, composed of NPK and its variants with MgS, the yield of crude oil was predicted the best by amounts of nitrogen and zinc in seeds. The positive correlation of nitrogen with oil yield indicates on its high efficiency, supported by magnesium sulfate.

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