

The physical and chemical properties of camelina (*Camelina sativa* (L.) Crantz) seeds subjected to sulfur fertilization

Ewa Ropelewska^{1,*} and Krzysztof J. Jankowski²

¹ Fruit and Vegetable Storage and Processing Department, Research Institute of Horticulture, Konstytucji 3 Maja 1/3, 96-100 Skierniewice, Poland

² Department of Agrotechnology, Agricultural Production Management and Agribusiness, Faculty of Environmental Management and Agriculture, University of Warmia and Mazury in Olsztyn, M. Oczapowskiego 8, 10-719 Olsztyn, Poland

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Abstract – Camelina is an oilseed crop. Seeds may have an application in various industries. Sulfur applied to soil can increase the seed yield. However, there is insufficient information on the optimal dose of sulfur fertilization that provides the best physical and chemical properties of seed. The aim of this study was to determine the physical and chemical properties of camelina seeds subjected to sulfur fertilization at 0 (control), 15, 30 kg S ha⁻¹ applied as potassium sulfate. The content of crude fat of camelina seeds ranged from 346.4 g kg⁻¹ dm (30 kg S ha⁻¹) to 360.9 g kg⁻¹ dm (control plots). The selected shape factors and linear dimensions of camelina seeds were significantly positively affected by sulfur fertilizer applied at 30 kg S ha⁻¹. The results can be used to select the optimal dose of sulfur fertilizer, which has the greatest positive effect on camelina seed properties. Seeds with the best characteristics are desirable for the processing. The optimal dose of sulfur fertilizer is 30 kg S ha⁻¹. It may be useful in practice that the selected linear dimensions and shape factors of seeds were significantly positively affected by sulfur fertilizer applied at 30 kg S ha⁻¹.

Keywords: camelina seeds / sulfur fertilizer / physical properties / chemical properties

Résumé – Propriétés physiques et chimiques des graines de cameline (*Camelina sativa* (L.) Crantz) soumises à une fertilisation au soufre. La cameline est une plante oléagineuse. Les graines peuvent être utilisées dans diverses industries. Une fertilisation au soufre, *via* le sol, peut augmenter le rendement des graines. Toutefois, on ne dispose pas d'informations suffisantes sur la dose optimale de soufre qui permet d'obtenir les meilleures propriétés physiques et chimiques des semences. L'objectif de cette étude était de déterminer les propriétés physiques et chimiques des graines de cameline soumises à une fertilisation au soufre à 0 (témoin), 15, 30 kg S ha⁻¹ appliquée sous forme de sulfate de potassium. La teneur brute en lipides des graines de cameline variait de 346,4 g kg⁻¹ dm (30 kg S ha⁻¹) à 360,9 g kg⁻¹ dm (parcelles témoins). Les caractéristiques de forme retenues et les dimensions linéaires des graines de cameline ont été positivement influencées, et ce de manière significative, par l'engrais au soufre appliqué à 30 kg S ha⁻¹. Les résultats obtenus s'avèrent utiles pour sélectionner la dose optimale d'engrais soufré qui améliore le plus les propriétés des graines de cameline. Les graines présentant les meilleures caractéristiques sont souhaitables pour la transformation. La dose optimale d'engrais soufré est de 30 kg S ha⁻¹. Il peut être utile dans la pratique que les dimensions linéaires et les caractéristiques de forme des graines sélectionnées aient été significativement influencés positivement par l'engrais soufré appliqué à 30 kg S ha⁻¹.

Mots clés : graines de cameline / engrais soufré / propriétés physiques / propriétés chimiques

*Correspondence: ewa.ropelewska@inhort.pl

1 Introduction

Camelina [*Camelina sativa* (L.) Crantz, *Brassicaceae*] is a spring annual or winter annual plant, which was grown in south-eastern Europe already in the late Neolithic period (Putnam *et al.*, 1993). Camelina was a popular oilseed crop in the European mainland and Scandinavia in the Iron Age. The species is well adapted to semi-arid climates (Mulligan, 2002). Mostly spring varieties of camelina are cultivated in Europe (Akk and Ilumae, 2005). In comparison with oilseed rape, mustard, flax and sunflower, camelina has higher drought and cold tolerance and it is characterized by lower production costs (fertilizers, pesticides) (Zubr, 1997; Lafferty *et al.*, 2009). Its growing season is short (85–100 days) (Shukla *et al.*, 2002). The oil content of camelina seeds can be equal to 350–450 g kg⁻¹ dm (Zadernowski *et al.*, 1999; Gugel and Falk, 2006; Urbaniak *et al.*, 2008, Jiang *et al.*, 2013; Malhi *et al.*, 2014). Unsaturated fatty acids have a high share (85–90%) of the total fatty acid pool in camelina oil (Zubr, 1997; Goffman *et al.*, 1999; Zadernowski *et al.*, 1999; Abramovic and Abram, 2005). Polyunsaturated fatty acids (PUFAs) – linoleic acid and α -linolenic acid account for approximately 50% of total fatty acids, including 38% of C_{18:3} and 15% of C_{18:2} (Skjervold, 1993; Zubr, 2003). n-3 PUFAs play a key role in eye and brain development, and in cardiovascular disease prevention (Nettleton, 1991). ALA-rich diets reduce the risk of myocardial infarction, cancer and cardiovascular disease (Zubr, 2003). Due to high contents of omega-3 fatty acids and α -linolenic acid (Ruxton *et al.*, 2007), camelina oil can be used in food production (Pilgeram *et al.*, 2007).

Camelina protein contains essential amino acids such as isoleucine, histidine, leucine, methionine, lysine, phenylalanine, valine and threonine. Camelina oil cake and meal are valuable feedstuffs and a rich source of fat and protein for poultry diets (Zubr, 1997). Dietary supplementation with camelina oil can increase the content of n-3 PUFAs in eggs without the unpleasant flavor typical of flaxseed oil (Rokka *et al.*, 2002). Camelina meal has a high content of energy and protein and can be used as forage for pigs and ruminants (Matthaus and Zubr, 2000). In the vegetative and generative organs are accumulate glucosinolates (GLS) (Verkerk *et al.*, 2009). Lošák *et al.* (2011) found that soil application of sulfur increased camelina seed yield by around 10%. It should be noted that sulfur applied to soil increases the seed yield of *Brassica* crops particularly on sulfur-deficient soils (Jankowski *et al.*, 2015). In soils characterized by moderate sulfur concentrations, sulfur fertilization exerts no yield-forming effects in camelina cultivation (Lošák *et al.*, 2011; Solis *et al.*, 2013; Sintim *et al.*, 2015). Mentioned literature data indicate that sulfur fertilization can increase seed yield. However, there is insufficient information on the optimal dose of sulfur fertilization that provides the best physical and chemical properties of seed. Such information may be relevant for the storage and processing of seeds. Therefore, knowledge about the effects of sulfur fertilization on the different physical and chemical characteristics of seeds should be supplemented in order to choose the optimal dose.

The aim of this study was to determine the physical and chemical properties of camelina seeds subjected to sulfur fertilization at 0 (control), 15, 30 kg S ha⁻¹ and finding out the optimal dose. The physical (thousand seed weight, densities,

porosity, width, length, surface area, object boundary specific perimeter, maximum Martin radius, folding factor, mean thickness factor, compactness, roundness, Blair–Bliss coefficient) and chemical properties (crude fat content, crude protein content) of seeds were determined.

2 Materials and methods

2.1 Field experiment

Spring camelina seeds were produced in 2018, in an experiment conducted in Bałcyny (N = 53°35'46.4"; E = 19°51'19.5") at the station owned by the University of the Warmia and Mazury in Olsztyn. Before sowing, different rates of sulfur (kg ha⁻¹): 0, 15, 30 were applied by broadcasting as potassium sulfate (samples: control, 15 kg S ha⁻¹, 30 kg S ha⁻¹).

The experiment was carried out in three replications. Plot size of 15 m² was used. All doses of sulfur fertilizer presented in kg S ha⁻¹ were converted into the dose per m² and applied for the plot. The preceding crop was spring wheat. The soil was skimmed, winter plowed and mechanical loosened before pre-sowing. The soil characteristics were detailed described by Jankowski *et al.* (2019). Seeds of spring camelina cv. “Omega” were sown in April. Plot seeder at a density of 450 pure live seeds m⁻², to a depth of 1.0–1.5 cm, spacing of 11 cm was used. 80 kg N ha⁻¹ in the form of ammonium nitrate, 45 kg P₂O₅ ha⁻¹ as enriched superphosphate, and 90 kg ha⁻¹ K₂O in the form of potassium sulfate and potash salt were applied immediately before sowing. 40 kg N ha⁻¹ as ammonium nitrate was applied at the beginning of inflorescence emergence of camelina. Butisan 400 SC at 2.0 dm³ ha⁻¹ (800 g ha⁻¹ metazachlor) was applied directly after sowing. Spring camelina was harvested at physiological maturity.

2.2 Physical properties

Thousand seed weight [g] was calculated (ISTA, 2013). Bulk density [g cm⁻³] was determined using Standard EN ISO 7971-3:2019. True density [g cm⁻³] was measured using Standard PN-EN 1097-6:2013 and was calculated based on the equation (1):

$$\rho_t = \frac{m_0}{m_0 - m_1} * \rho_c, \quad (1)$$

where: ρ_t – true density; m_0 – seed mass in air; m_1 – seed mass in liquid; ρ_c – liquid density at a known temperature.

Porosity [%] was calculated using the equation (2):

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t} * 100\%, \quad (2)$$

where: ε is porosity, ρ_t is true density, ρ_b is bulk density.

The measurements of each parameter were carried out in five replicates.

2.3 Geometric parameters

The computer image analysis with the use of a flatbed scanner was applied to determine the geometric parameters of camelina seeds. Scaling with a caliper was performed prior to

Table 1. Physical properties of camelina seeds subjected to sulfur fertilization.

Sample	1000 seed weight, g	Bulk density, g cm ⁻³	True density, g cm ⁻³	Porosity, %
0 kg S ha ⁻¹	1.41 ^a	0.681 ^a	1.090 ^a	37.5 ^a
15 kg S ha ⁻¹	1.42 ^a	0.679 ^a	1.085 ^a	37.4 ^a
30 kg S ha ⁻¹	1.42 ^a	0.680 ^a	1.087 ^a	37.4 ^a

a, b denote homogeneous groups, $P \leq 0.05$.

Table 2. Linear dimensions of camelina seeds subjected to sulfur fertilization.

Sample	L , mm	S , mm	F , mm ²	U_g , mm	M_{max} , mm
0 kg S ha ⁻¹	1.99 ^a	1.14 ^a	1.90 ^a	13.78 ^a	1.03 ^a
15 kg S ha ⁻¹	2.01 ^a	1.15 ^a	1.92 ^a	13.79 ^a	1.04 ^a
30 kg S ha ⁻¹	2.04 ^b	1.17 ^b	2.00 ^b	14.04 ^b	1.05 ^b

a, b denote homogeneous groups, $P \leq 0.05$.

L : length; S : width; F : surface area; U_g : object boundary specific perimeter; M_{max} : maximum Martin radius.

the acquisition of images. Images of seeds from plots without fertilization and with different rates of sulfur fertilizer were acquired at a resolution of 800 dpi. The images were analyzed using MaZda software (Szczypiński *et al.*, 2009). Geometric parameters (linear dimensions and shape factors) were calculated for each seed.

2.4 Chemical properties

Total protein and crude fat of camelina seed were calculated. The properties of seeds were determined using the NIR Systems 6500 monochromator (FOSS NIR Systems Inc., USA) with a reflectance module. About 5 g of seeds were placed into a cup and scanned. The partial least squares (PLS) calibrations was used to predict the results. The reference data for total protein was from the Kjeldahl method and for crude fat from Soxhlet extraction method.

2.5 Statistical analysis

Statistica 12.0 (StatSoft Inc., Tulsa, USA) was used for analysis of results. The differences in the physical, geometric and chemical parameters of seeds were determined using a significance level of $P \leq 0.05$. The normality of distribution was checked using Lilliefors, Shapiro–Wilk and Kolmogorov–Smirnov tests, and the homogeneity of variance was determined using the Brown–Forsythe test and Levene’s test. The Newman–Keuls parametric test and the Kruskal–Wallis non-parametric test were applied to analyze normally and non-normally distributed variables, respectively.

3 Results and discussion

3.1 Physical properties of camelina seeds

The mean values of selected physical properties, such as: 1000 seed weight, bulk density, true density and porosity of camelina seeds are presented in Table 1. The 1000 seed weight ranged from 1.41 g (control) to 1.42 g (15 kg S ha⁻¹,

30 kg S ha⁻¹). In camelina seeds, significant differences in the values of bulk and true densities density or porosity were determined between plots with and without sulfur fertilizer. All samples of camelina seeds formed another homogenous group. The bulk density of camelina seeds ranged from 0.679 g cm⁻³ (15 kg S ha⁻¹) to 0.681 g cm⁻³ (control), their true density ranged from 1.085 g cm⁻³ (15 kg S ha⁻¹) to 1.090 g cm⁻³ (control) and porosity ranged from 37.4 (15 kg S ha⁻¹, 30 kg S ha⁻¹) to 37.5% (control). The values of the 1000 seed weight of camelina, determined in our study, are similar to those reported by Gugel and Falk (2006) at 1.2–1.4 g, Guy *et al.* (2014) at 1.15–1.46 g, and Pecchia *et al.* (2014) at 0.98–1.56 g. Solis *et al.* (2013) and Lošák *et al.* (2011) demonstrated that sulfur fertilization had no significant effect on the 1000 seed weight of camelina. The values of bulk density of camelina seeds obtained in the current study are comparable with those reported by Guy *et al.* (2014) at 636–666 kg m⁻³. The bulk density and true density of camelina seeds are also similar to the values reported for the seeds of other oilseed plants, *e.g.* rapeseed with bulk density of 0.664–0.675 g cm⁻³ (Ropelewska *et al.*, 2017) and 0.593–0.676 g cm⁻³ (Izli *et al.*, 2009), and true density from 1.029 to 1.074 g cm⁻³ (Ropelewska *et al.*, 2017), 1.015–1.091 g cm⁻³ (Izli *et al.*, 2009) or mustard with bulk density determined at 0.729–0.755 g cm⁻³ (Ropelewska *et al.*, 2018) and 0.785–0.906 g cm⁻³ (Grewal and Singh, 2016), and true density at 1.169–1.203 g cm⁻³ (Ropelewska *et al.*, 2018) and 0.924–1.275 g cm⁻³ (Grewal and Singh, 2016). Ropelewska and Jankowski (2020) reported that bulk density of crambe seeds was in the range of 0.619–0.625 g cm⁻³, and true density ranged from 0.964 g cm⁻³ to 0.979 g cm⁻³.

3.2 Geometric properties of camelina seeds

The values of selected linear dimensions of seeds are presented in Table 2. Sulfur fertilization resulted in the changes in the width (S), length (L), surface area (F), object boundary specific perimeter (U_g) and maximum Martin radius (M_{max}) of camelina seeds. In seeds, L ranged from 1.99 to 2.04 mm,

Table 3. Shape factors of camelina seeds subjected to sulfur fertilization.

Sample	W_4 , –	W_5 , –	W_6 , –	W_{13} , –	R_B , –
0 kg S ha ⁻¹	2.68 ^a	0.75 ^a	0.58 ^a	1.08 ^a	1.27 ^a
15 kg S ha ⁻¹	2.67 ^b	0.75 ^a	0.58 ^a	1.07 ^a	1.28 ^a
30 kg S ha ⁻¹	2.67 ^{ab}	0.76 ^b	0.57 ^b	1.05 ^b	1.30 ^b

a, b denote homogeneous groups, $P \leq 0.05$.

W_4 : folding factor; W_5 : mean thickness factor; W_6 : compactness; W_{13} : roundness; R_B : Blair–Bliss coefficient.

S ranged from 1.14 to 1.17 mm, F ranged from 1.90 to 2.00 mm², U_g ranged from 13.78 to 14.04 mm, and M_{max} ranged from 1.03 to 1.05 mm. The highest S , L , F , U_g and M_{max} were determined in the case of seeds fertilized with the 30 kg S ha⁻¹, and the lowest values of these parameters were observed in sample without sulfur fertilizer (0 kg S ha⁻¹). The control seeds and the sample fertilized with 15 kg S ha⁻¹ formed a homogenous group with respect to the values of all parameters. The sample fertilized with 30 kg S ha⁻¹ formed the second homogenous group. Due to their ability to biosynthesize GLS, *Brassica* crops have high sulfur requirements compared with non-cruciferous crops (Jankowski *et al.*, 2015). Wysocki *et al.* (2013) demonstrated that the application of sulfur at 22 kg ha⁻¹ increased camelina seed yield by around 1–6%. Jiang *et al.* (2013) found that sulfur fertilizer applied at 25 kg ha⁻¹ increased camelina seed yield by approximately 7%. The high sulfur requirements of camelina may be the reason for the statistically significant increase in linear dimensions of seeds caused by the highest dose of sulfur fertilizer (30 kg S ha⁻¹) in our research.

The shape factors of camelina seeds, including folding factor (W_4), mean thickness factor (W_5), compactness (W_6), roundness (W_{13}) and Blair–Bliss coefficient (R_B) were also calculated (Tab. 3). In seeds, the values of shape factors were as follows: W_4 –2.67–2.68, W_5 –0.75–0.76, W_6 –0.57–0.58, W_{13} –1.05–1.08, and R_B –1.27–1.30. The 30 kg S ha⁻¹ sample was characterized by the highest mean values of W_5 and R_B , and the control sample had by the lowest values of these parameters. The values of the remaining parameters (W_4 , W_6 and W_{13}) were highest in the control sample and lowest in the 30 kg S ha⁻¹ sample. The control and 15 kg S ha⁻¹ samples formed one homogeneous group with respect to the values of W_5 , W_6 , W_{13} and R_B .

3.3 Chemical properties of camelina seeds

The mean values of chemical properties, including the crude fat content and crude protein content of camelina seeds are presented in Table 4. Seeds from the control plots had the highest crude fat content (360.9 g kg⁻¹ dm) and the lowest crude protein content (255.1 g kg⁻¹ dm). The sample fertilized with the highest rate of sulfur (30 kg S ha⁻¹) had the lowest crude fat content (346.4 g kg⁻¹ dm) and the highest crude protein content (256.7 g kg⁻¹ dm). Lošák *et al.* (2011) and Obeng *et al.* (2016) demonstrated that sulfur fertilization did not significantly affect the chemical properties of camelina seeds, including oil content and protein content. In a study by Joshi *et al.* (2017), the sulfur fertilization did not cause significant changes in oil content of camelina seeds. However,

Table 4. Chemical properties of camelina seeds subjected to sulfur fertilization.

Sample	Crude fat, g kg ⁻¹ DM	Crude protein, g kg ⁻¹ DM
0 kg S ha ⁻¹	360.9 ^a	255.1 ^a
15 kg S ha ⁻¹	359.4 ^a	255.8 ^a
30 kg S ha ⁻¹	346.4 ^b	256.7 ^a

a, b denote homogeneous groups, $P \leq 0.05$.

Wielebski (2006) reported that sulfur fertilization may significantly decrease the crude fat content and increase the total protein content in winter oilseed rape seeds. Sulfur is important in plant nutrition and it affects nitrogen management determining the size and quality of the seed yield. Sulfur is also a component of glucosinolates and affects the amount of these substances. An increase in sulfur fertilization can also increase the content of methionine, cystine and lysine (Wielebski, 2006). Jankowski *et al.* (2005) revealed that the application of sulfur used during the growing season of oilseeds may result in a reduction in the crude fat content (oil content) in seeds. It may be caused by the positive effect of sulfur on the yield and the occurrence of the diluting the ingredients in an increased yield. However, the decrease in the fat content did not affect the decrease in the fat yield per 1 ha.

Research provided new knowledge on the physical and chemical properties of seed subjected to sulfur fertilization at various doses. The results supplemented information on the effect of sulfur on camelina cultivation. It has been demonstrated that in addition to increasing seed yield, sulfur fertilization can also improve seed quality. This information may be useful for the storage and processing of seeds and may have an application in various industries.

Mineral fertilization is a key agronomic operation affecting the yield and quality of crop plants. Sulfur is an essential nutrient for plants of the family *Brassicaceae*. Sulfur fertilizers (similarly to nitrogen fertilizers) contribute to a decrease in the oil content and an increase in the protein content of seeds in *Brassica* crops. The total nitrogen + sulfur fertilization level usually remains constant, regardless of the rate of sulfur fertilizer. *Brassica* crops are a source of both edible oil and high-protein feed (fat-free seed residues), therefore a slight modification of the proportions of sulfur and nitrogen (which does not change the total fertilization level) has no significant effect on the economic importance and uses of seeds. Due to their physical properties, camelina seeds are suitable for processing in the oleochemical industry, and the recommended

rate of sulfur fertilizer is 30 kg ha⁻¹. In order to develop fertilizer recommendations for agricultural practice and the oilseed processing industry, further research is needed to investigate the correlation between sulfur fertilization vs. the physical properties and chemical composition of camelina seeds (and other *Brassica* crops).

4 Conclusions

A high amount of sulfur fertilizer increased the linear dimensions and shape factors (width, length, surface area, object boundary specific perimeter, maximum Martin radius, mean thickness factor, compactness, roundness, Blair–Bliss coefficient) of camelina seeds and reduced the crude fat amount. Sulfur fertilization did not significantly affect the 1000 seed weight, bulk and true densities or porosity of camelina seeds.

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