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Reaction of Camelina (*Camelina sativa* (L.) Crantz) to Different Foliar Fertilization

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Abstract: Camelina (*Camelina sativa* (L.) Crantz) is an oil plant that can increase farmland biodiversity in many parts of the world. In addition to food importance, it is a good alternative in biofuel production. The aim of the experiment was to evaluate the response of camelina, the variety Śmiłowska (spring form), to various foliar fertilization. The combined application of three fertilizers had the most positive effect on the tested features and economic result: urea (46% N), magnesium sulfate (16% MgO + 32% SO_3), and Plonvit R (multi-component fertilizer). The obtained increase in seed yield after the application of the above variant was 0.54 t ha^{-1}, i.e., 37.5% compared to the control. The remaining fertilization combinations did not have a significant effect on seed yield, which amounted on average to 1.66 t ha^{-1}. The yield of fat and protein amounted to 0.68 t·ha^{-1} and 0.42 t ha^{-1}, respectively, and was strongly correlated with seed yield. The yielding of the variety Śmiłowska was stable over the years of the study. The combined use of three foliar fertilizers (variant H) increased the SPAD (soil plant analysis development) and LAI (leaf area index) values compared to the control. The application of urea alone reduced crude fat content in the seeds.

Keywords: macroelements; micronutrients; SPAD; LAI; yield component; yield; chemical composition

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1. Introduction

Camelina is a known oil plant from the family *Brassicaceae* Burnett. In recent years, interest in the cultivation of this species has increased. This is due to the high tolerance of camelina to unfavorable environmental conditions and the possibility of versatile crop utilization [1,2]. According to Román-Figueroa et al. [3], a special feature of this plant is its easy adaptation to various soil and climatic conditions. Both spring and winter varieties of this species are cultivated [4,5]. Kurasiak-Popowska et al. [6] reported that camelina had a great potential for biofuel and food production. Average yields of the latter authors were 1.3 t ha^{-1} for the spring form and 1.9 t ha^{-1} for the winter form. In Poland, camelina has little economic importance, but it can be a good alternative to the commonly grown oilseed rape. Mauri et al. [7] showed that the camelina yield depends on the varieties and years of research. According to Krzyżaniak et al. [8], new, more fertile varieties will contribute to the increase in camelina importance. The best of them already provide a seed yield above 2 t ha^{-1} with a fat content above 40%. Kim et al. [9] concluded that transgenic varieties intended for biodiesel may prove particularly useful in unfavorable environmental conditions. Berti et al. [10] and Luo et al. [11] argued that the improvement of genetic characteristics of this species was the basis for further development of the production of this agriculturally valuable plant. In the wake of new varieties, their agriculture treatments should also be improved. Bujnovský et al. [12] indicated that camelina is a good alternative mainly as a raw material for biofuel production. Such a cultivation may be located in worse environmental conditions and in fallow areas. Sidhu et al. [13] reported that the advantage of camelina is its beneficial effect on the natural environment; for example, reduction of soil erosion. Załuski et al. [14] have concluded that the observed climate changes result in the search for species that can be cultivated in less favorable environmental conditions and camelina has been indicated as one of such plants. Hossain et al. [15]

showed, however, that the cultivation of oilseed rape for biofuel was more efficient than mustard or camelina under water shortage conditions. Davis et al. [16] also reported that oilseed rape was competitive compared to camelina on both clay and sandy soils. Thus, in some regions, camelina may not be as useful as it is commonly believed. Tulkubayeva and Vasin [17] drew attention in this aspect to the role of agriculture measures, which should be adapted to local soil and climatic conditions. This will allow the obtaining of a greater potential of camelina yielding. Leclère et al. [18] showed that the lack of agronomic knowledge often hampers popularization of new crops in current farming systems. Jiang and Caldwell [19] have concluded that camelina is usually considered a low-input crop. They proved in a field experiment that it reacted positively to high nitrogen doses, even up to 200 kg ha^{-1}, but this mainly concerned new and improved varieties. In regard to agriculture practices, optimal camelina fertilization should be considered particularly important [20–22]. Similarly to other crops of the family *Brassicaceae* Burnett, camelina responds favorably to nitrogen fertilization. Li et al. [23] showed, however, that increased nitrogen fertilization of camelina resulted in higher N_2O emissions. Therefore, optimal doses of nitrogen fertilizers should be selected in plant crops to avoid negative impact on the environment. The recommended nitrogen doses for camelina vary and range from 34 kg ha^{-1} [24] to 60 kg ha^{-1} [25] and more [19,26,27]. In a study of Malhi et al. [28], camelina responded favorably to high nitrogen doses. Therefore, the question arises whether camelina should be treated as a low-input cultivation under all conditions, without application of an appropriate level of nitrogen fertilization. Solis et al. [29] confirmed that camelina reacted mainly to nitrogen fertilization and to a much lesser extent to sulfur and phosphorus. Therefore, they believed that this plant could use higher nitrogen doses when grown under environmental conditions that would maximize its yield potential. Jiang et al. [30] reported that fertilizing camelina with nitrogen increased seed yield, protein content, protein yield, and the content of polyunsaturated fatty acids, but reduced the content of oil and monounsaturated fatty acids. In turn, sulfur was shown to have a positive effect on the size and quality of camelina yield, but only when the level of nitrogen fertilization was high. Afshar et al. [31] showed that nitrogen fertilization of camelina reduced fat content in seeds but increased the yield of this nutrient per hectare. In the discussed aspect, Kurasiak-Popowska et al. [32] recognized the importance of research not only on the quantity, but also quality of camelina yield. Jiang et al. [33] stated that the quality of camelina seeds was determined by variety selection, environmental factors, and agriculture practices, including fertilization. Amiri-Darban et al. [34] obtained the maximum camelina yield of seeds and fat after irrigation and combined fertilization with potassium sulfate (75 kg ha^{-1}) + ammonium sulphate (75 kg ha^{-1}). Therefore, it is justified to conduct research on the improvement of fertilization recommendations for camelina, which will increase its production and economic importance. There is little information in the literature on foliar fertilization of camelina. The available data concern mainly soil fertilization with nitrogen and sulfur, and with boron as a micronutrient. Kumari et al. [35] showed that the combined fertilization of 40 N kg ha^{-1} and 20 S kg ha^{-1} allowed the obtaining of the highest camelina seed and oil yield. In the study of Jiang et al. [30], the optimal nitrogen dose ranged from 120 to 160 kg ha^{-1}. The application of sulfur was justified but only when the nitrogen level was high. In turn, Wysocki et al. [36] reported that optimal nitrogen doses depended on rainfall and soil fertility and ranged from 0 to 90 kg ha^{-1}. On the other hand, sulfur fertilization was not justified at any location. Kumari et al. [37] showed that foliar application of boron resulted in a higher camelina yield as compared to the control. Moreover, the application of boron with urea increased oil content of seeds. Khan et al. [38] reported that foliar or soil boron application resulted in a higher quantitative and qualitative yield of camelina seeds.

The aim of the research was to determine the reaction of the camelina variety Śmiłowska (spring form) to different foliar fertilization with macro- and microelements. The research hypothesis assumed that the applied fertilizer combinations would have a modifying effect on the size and quality of seed yield and would be economically justified.

2. Materials and Methods

2.1. Field Experiment

The field experiment was carried out in 2016–2018 at the Experimental Station for Variety Testing in Przecław (50°11′ N, 21°29′ E), Poland. It was a one-factor experiment with four replications. Different variants of camelina foliar fertilization in comparison to the control was the investigated factor, as shown in Table 1. The experiment was carried out on the variety Śmiłowska. It is a spring form, yielding well in the research area. It was bred at the Department of Genetics and Plant Breeding at the Poznań University of Life Sciences, Poland.

Table 1. Fertilization diagram.

Date of Plant Fertilization			
before sowing, soil fertilization (kg·ha^{-1})	beginning of budding (BBCH 55), foliar fertilization		
	variant	fertilizer	dose per hectare
$50N + 40P_2O_5 + 60K_2O$	A	Control	-
	B	Urea	16.6 kg N
	C	Magnesium Sulfate heptahydrate	2.4 kg MgO + 4.8 kg·SO_3
	D	Plonvit R	2 l
	E	Urea + Magnesium Sulfate heptahydrate	16.6 kg N + 2.4 kg MgO + 4.8 kg·SO_3
	F	Urea + Plonvit R	16.6 kg N + 2 l
	G	Magnesium Sulfate heptahydrate + Plonvit R	2.4 kg MgO + 4.8 kg·SO_3 + 2 l
	H	Urea + Magnesium Sulfate heptahydrate + Plonvit R	16.6 kg N + 2.4 kg MgO + 4.8 kg·SO_3 + 2 l

Before sowing, soil mineral fertilization was applied. The doses of nitrogen, phosphorus, and potassium were 50 kg ha^{-1} (ammonium nitrate 34% N), 40 kg ha^{-1} (superphosphate 24% P_2O_5), and 60 kg ha^{-1} (potassium salt 60% K_2O), respectively.

The following were used for foliar fertilization: urea (46% N), magnesium sulfate heptahydrate (MgO 16% + SO_3 32%), and the compound fertilizer Plonvit R (N 15%, MgO 2.5%, SO_3 2.5%, B 0.5%, Cu 0.1%, Fe 0.5%, Mn 0.5%, Mo 0.005%, Zn 0.5%, and Ti 0.03%). Urea concentration in 100 L of water was 12%, and magnesium sulfate was 5%. Volume of the working solution was 300 dm^3 per ha.

Winter rye was the forecrop. The area of plots for harvest was 15 m^2. The sowing of seeds was carried out on the following days: 12.04.2016, 10.04.2017, and 13.04.2018. The planned plant density was 300 pcs/m^2. Row spacing was 24.5 cm and sowing depth was 1.5 cm. The BBCH scale (Biologische Bundesanstalt, Bundessortenamtund CHemische Industrie) was given according to Martinelli and Galasso [39]. On the day of sowing, the herbicide Butisan 400 SC (metazachlor) was applied at a dose of 2.5 dm^3 ha^{-1}. At the BBCH 31 stage, the fungicide Amistar Gold Max (azoxystrobin + difenoconazole) was applied at a dose of 1 dm^3 ha^{-1}. Pests were not controlled due to the occasional occurrence.

Soil plant analysis development (SPAD) was measured with a SPAD 502P chlorophylometer (Konica Minolta, Inc., Tokyo, Japan). Leaf area index (LAI) measurements were performed using a Meter LP-80 AccuPAR apparatus (Pullman, WA, USA). Index SPAD and LAI were measured in the BBCH 60 stage.

The seeds were harvested using a plot harvester in July. Seed yield was calculated per 1 ha at 15% moisture.

2.2. Weather and Soil Conditions

Weather conditions were given according to the readings of the Experimental Station for Variety Testing in Przecław. The experiment was established in the sandy loam, Gleic Fluvisol—FLgl [40]. Soil pH was neutral, N_{min} was low, and the humus content was average. Soil abundance in available phosphorus was very high, potassium—high, magnesium—very high, and sulfur—low, as shown in Table 2. The content of micronutrients determined in the soil was medium, except for low boron. The analysis of soil samples was performed in the accredited laboratory of the Regional Chemical and Agricultural Station in Rzeszów (Polish standards).

Table 2. Chemical properties of soil at the depth of 0–60 cm.

Measurement		2016	2017	2018
pH in KCl		6.8	6.7	7.0
N_{min} kg ha^{-1}		56	53	58
Humus %		1.2	1.6	1.4
P_2O_5	mg·100 g^{-1} of Soil	24.8	21.9	25.3
K_2O		21.6	23.0	21.2
Mg		11.1	14.9	10.3
S-SO_4		1.7	1.8	1.7
B	mg·1000 g^{-1} of Soil	1.4	2.1	0.9
Zn		15.6	17.5	16.3
Cu		6.2	4.2	5.5
Fe		3567.1	2504.3	3767.9
Mn		563.7	463.2	656.8

2.3. Chemical Analysis

The content of total protein and crude fat in seeds was determined using the NIRS (Near-infrared spectroscopy) method in near infrared on an FT NIR MPA Bruker spectrometer (Billerica, MA, USA). Protein and fat yield per ha were calculated based on seed yield and the percentage of a given component in seeds. Magnesium and microelements were determined at the Laboratory of the Faculty of Biology and Agriculture, the University of Rzeszow. To determine magnesium and microelements, plant samples were mineralized in a mixture of concentrated acids HNO_3:$HClO_4$:HS_2O_4 in the 20:5:1 ratio, in an open system, in a Tecator heating block. The contents of Mg, Zn, Mn, Cu, and Fe in the obtained mineralized elements were determined by atomic absorption spectroscopy (FAAS), using the apparatus Hitachi Z-2000 (Tokyo, Japan).

2.4. Economic Analysis

Prices for economic calculations are given for 2019. Exchange rate: 1 EUR = 4.3 PLN. Costs of foliar fertilizers are given in accordance with the offer of the selling companies and calculated per 1 ha. Cost of foliar spraying—9.3 EUR per 1 ha. The purchase price for camelina seeds was 162.25 EUR per ton.

2.5. Statistical Analysis

The results of the study were statistically analyzed with the analysis of variance (ANOVA), using the statistical software TIBCO Statistica 13.3.0 (StatSoft, Tulsa, OK, USA). Significance of differences between treatments was verified by Tukey's test.

3. Results and Discussion

3.1. Weather Conditions

Weather conditions were variable over the years of the study and had a modifying effect on some of the tested parameters. However, camelina yielding was stable over the years. In April and May 2017, low air temperatures were recorded with high rainfall. In 2018, the temperature in June was below the long-term average. Low rainfall was recorded in July 2017, April 2018, and in June each year, as shown in Figure 1. Many works [22,41,42] demonstrated that camelina yield depended on weather conditions. Zanetti et al. [1] pointed out that camelina gave a satisfactory yield under unfavorable environmental conditions, but when grown in more favorable conditions, it yielded significantly better. Pan et al. [43] reported that soil water availability had a significant impact on nitrogen uptake. Therefore, camelina is more sensitive to water deficit than nitrogen shortage. Jiang et al. [33] added that weather conditions determined the quality of camelina seeds. At lower air temperatures, during generative development, they obtained an increase in seed fat content. Hossain et al. [44] confirmed that fat yield was higher in the years with higher rainfall combined with lower temperature during the maturation of camelina seeds.

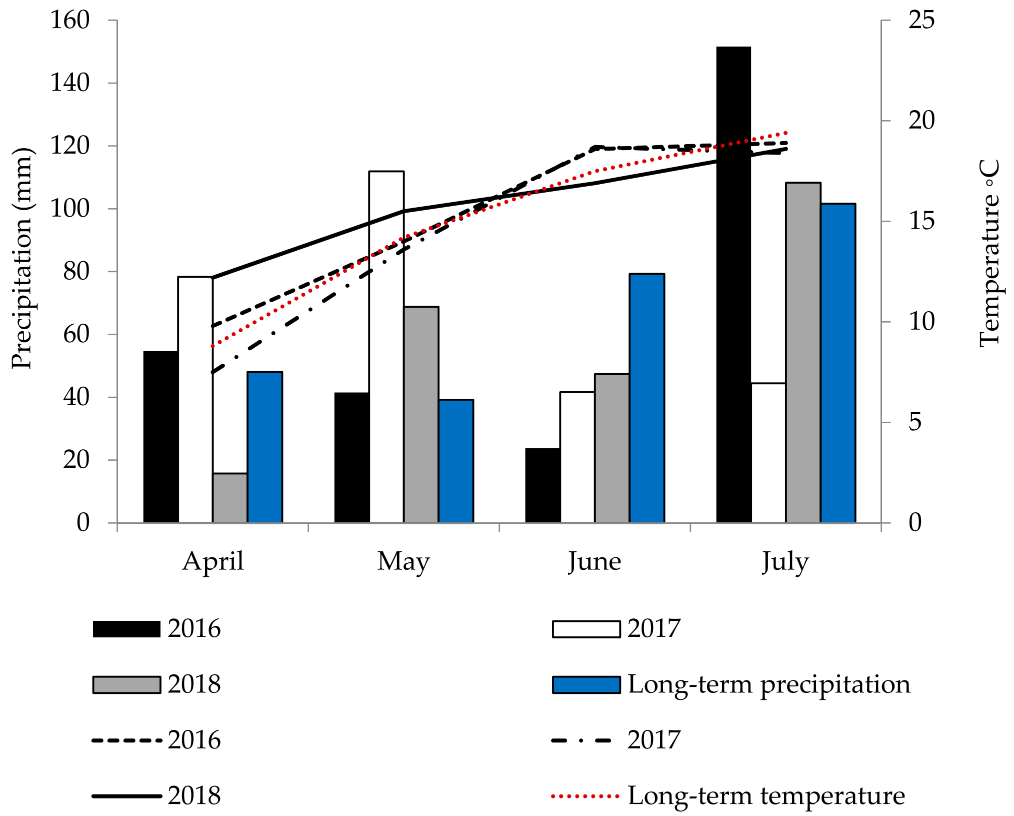

Figure 1. Mean monthly air temperature and total rainfall.

3.2. Results of Field and Biometric Measurements

Foliar fertilization had no effect on plant density before harvesting. On average, there were 198 plants per 1 m^2. The number of plants per area unit varied significantly during the years of research. The highest number of siliquae on the plant was obtained after applying urea or urea combined with other foliar fertilizers. The application of magnesium sulfate and/or Plonvit R had no effect on this parameter in comparison to the control. In 2017, the number of siliquae per plant was the lowest. A significant interaction was obtained between fertilization (F) and years (Y) in the case of the discussed feature. The applied variants of foliar fertilization did not modify the number of seeds in the siliqua. On the other hand, the studied trait was variable during the study years. TSW (Thousand seed weight) was most favorably influenced by the application of a combination of three foliar fertilizers (H). Robust seeds were also obtained after the application of urea with magnesium sulfate or urea with Plonvit R. TSW was 1.03 g on average and did not vary over the years of the study.

The application of three fertilizers in one spraying (urea, magnesium sulfate, and Plonvit R) significantly increased seed yield. The obtained difference was 0.54 t ha^{-1}, i.e., 37.5% compared to the control. The remaining fertilization variants did not significantly modify camelina yield in relation to the control. The average yield in the experiment was 1.66 t ha^{-1} and it did not vary in the years of the study, as shown in Table 3.

Table 3. Yield components and seed yield.

Variant [1]	Plant Density before Harvest (pcs.·m^{-2})	Number of Silicles per Plant	Number of Seeds per Silicle	Thousand Seed Weight (g)	Seed Yield (t·ha^{-1})
Foliar fertilization (F)					
A	198	86.8 ^{b}	8.75	0.96 ^{c}	1.44 ^{b}
B	196	96.3 ^{a}	8.75	1.01 ^{bc}	1.67 ^{ab}
C	198	88.6 ^{b}	8.75	0.98 ^{c}	1.50 ^{ab}
D	197	87.8 ^{b}	8.83	0.99 ^{c}	1.51 ^{ab}
E	200	97.3 ^{a}	8.67	1.05 ^{abc}	1.77 ^{ab}
F	199	97.6 ^{a}	8.83	1.11 ^{ab}	1.90 ^{ab}
G	198	89.3 ^{b}	8.80	1.03 ^{bc}	1.60 ^{ab}
H	199	98.3 ^{a}	8.80	1.15 ^{a}	1.98 ^{a}
Year (Y)					
2016	208 ^{a}	95.3 ^{a}	8.25 ^{b}	1.03	1.67
2017	200 ^{b}	88.3 ^{b}	8.72 ^{ab}	1.05	1.63
2018	187 ^{c}	94.6 ^{a}	9.38 ^{a}	1.02	1.69
Mean					
2016–2018	198	92.7	8.78	1.03	1.66
ANOVA					
F	n.s.	***	n.s.	***	**
Y	***	***	*	n.s.	n.s.
FxY	n.s.	*	n.s.	n.s.	n.s.

[1]—see Table 1, ***, **, * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$, n.s.—non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters (a, b, c) in columns are statistically different for foliar fertilization.

Studies conducted so far [45,46] showed that camelina yield depended on many factors and ranged from 0.75 t ha^{-1} [47] to 2.51 t·ha^{-1} [26]. Marcheva [47] and Mohammed et al. [44] indicated the need for further work to improve genetic characteristics and yield of camelina. Končius and Karčauskiene [48] obtained low yields of camelina (0.38 t ha^{-1} to 0.83 t ha^{-1}) due to unfavorable weather conditions, i.e., droughts persisting throughout the spring. Stolarski et al. [22] reported that weather conditions in the year of the study determined the yield of camelina seeds.

Correct agriculture treatments are of great importance in camelina cultivation. Fertilization is one of the most important treatments. Camelina responds by increased seed yield mainly to nitrogen [25,27] and to a lesser extent to sulfur [26]. In the discussed aspect, De Imperial Hornedo et al. [21] demonstrated that camelina reacted favorably to both organic and mineral fertilization. Wysocki et al. [36] reported that camelina required about 12 N kg ha^{-1} per 100 kg of the expected seed yield. Jiang and Caldwell [19] stated that the number of branches and siliquae on the plant had a decisive influence on seed yield. They also showed that nitrogen fertilization was positively correlated with downy mildew development. However, seed yield was not significantly affected by this disease. Hossain et al. [15,44] considered some species of oil plants as good alternatives to those commonly grown. However, in the case of camelina, they obtained too little competitiveness compared to oilseed rape. Therefore, Johnson et al. [24] believed that further research is needed to increase camelina yield. First of all, agriculture practices regarding new varieties of this species should be improved.

3.3. Field Measurements

The combined application of three foliar fertilizers (H) increased the SPAD index value compared to the control. Such a relationship was not statistically proven in the case of other fertilization combinations. The SPAD index significantly differed over the years of the study. High SPAD readings were recorded in 2017, as shown in Figure 2. Fritschi and Ray [49] and Neupane et al. [50] believed that SPAD readings were useful but should have also been supplemented with other measurement techniques.

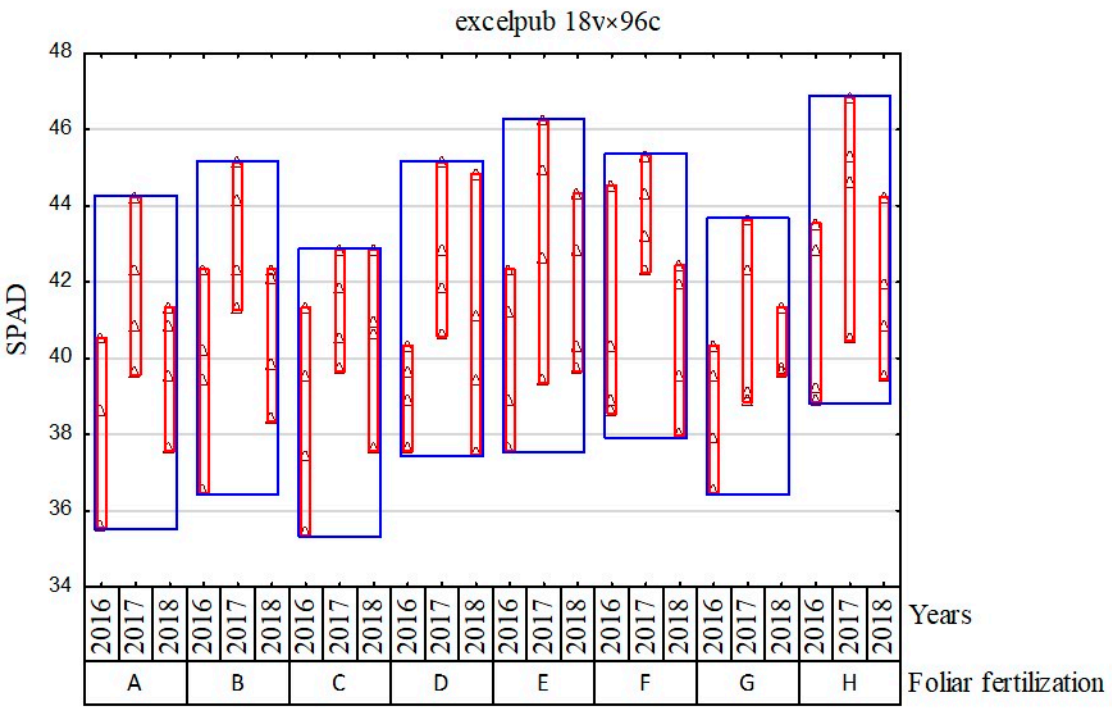

Figure 2. Soil plant analysis development (SPAD value). Description in Table 1.

The LAI index was most favorably influenced by the application of a combination of three foliar fertilizers (H). The LAI index was the highest in 2018, and significantly lower in 2017, as shown in Figure 3. Waraich et al. [51,52] demonstrated the usefulness of LAI measurements in the experiments involving camelina. Together with other measurements, they allowed the demonstration of how the plant reacted to the tested factor.

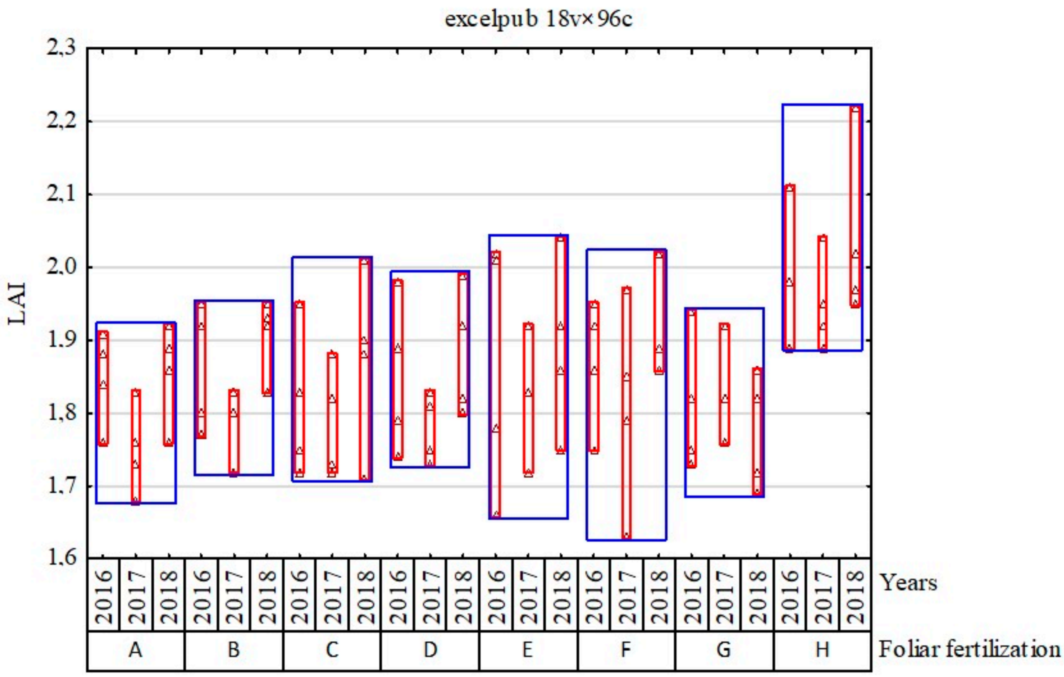

Figure 3. Leaf area index (LAI). Description in Table 1.

3.4. Chemical Composition

The application of urea alone reduced crude fat content in seeds. The content of this component ranged from 39.5% in 2016 to 41.8% in 2017. The interaction of fertilization (F) with years (Y) was obtained in the case of the discussed component. Fat yield was the highest after the application of three fertilizers and significantly lower in the control. The average productivity of the discussed component was 0.68 t ha^{-1} and did not differ over the years of the study.

Total protein content in seeds was not differentiated by foliar fertilization, but it varied over the study years. Total protein yield was significantly higher after the combined application of three fertilizers (H) compared to urea (B) and the control (A). Total protein yield was stable in the years of research. The obtained mean total protein content in camelina seeds was 25.1% dw, and the average total protein yield was 0.42 t ha^{-1}, as shown in Table 4.

Table 4. Chemical composition of seeds and yield of fat and protein.

Variant [1]	Fat Content (% DM)	Fat Yield (t·ha^{-1})	Protein Content (% DM)	Protein Yield (t·ha^{-1})
		Foliar fertilization (F)		
A	40.6 ^{a}	0.58 ^{b}	24.6	0.35 ^{c}
B	39.1 ^{b}	0.65 ^{ab}	25.6	0.42 ^{abc}
C	41.3 ^{a}	0.62 ^{ab}	24.8	0.37 ^{bc}
D	41.1 ^{a}	0.62 ^{ab}	24.9	0.38 ^{abc}
E	40.5 ^{a}	0.72 ^{ab}	25.0	0.44 ^{abc}
F	40.8 ^{a}	0.78 ^{ab}	25.3	0.48 ^{ab}
G	41.4 ^{a}	0.66 ^{ab}	24.9	0.40 ^{abc}
H	41.2 ^{a}	0.82 ^{a}	25.8	0.50 ^{a}

Table 4. *Cont.*

Variant [1]	Fat Content (% DM)	Fat Yield (t·ha^{-1})	Protein Content (% DM)	Protein Yield (t·ha^{-1})
		Year (Y)		
2016	39.5 ^{c}	0.66	25.6 ^{a}	0.43
2017	41.8 ^{a}	0.68	25.1 ^{a}	0.41
2018	41.0 ^{b}	0.69	24.4 ^{b}	0.41
		Mean		
2016–2018	40.8	0.68	25.1	0.42
		ANOVA		
F	***	**	n.s.	**
Y	***	n.s.	***	n.s.
FxY	*	n.s.	n.s.	n.s.

[1]—see Table 1, ***, **, * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$, n.s.—non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters (a, b, c) in columns are statistically different for foliar fertilization.

Krzyżaniak et al. [8] obtained similar results—fat content from 39.3 to 42.2% dw and fat yield from 0.69 to 0.93 t ha^{-1}. Toncea et al. [53] reported that camelina seeds contained 30.1–49.7% fat and additionally 18.87–21.97% protein. Jankowski et al. [26] showed that nitrogen reduced crude fat content in camelina seeds, while increased protein content. Solis et al. [28] and Urbaniak et al. [54] also obtained a negative correlation between fat content in seeds and nitrogen dose. Lošák et al. [55] concluded, however, that nitrogen fertilization increased the yield of fat and protein per hectare. The latter authors recommended the combined application of nitrogen and sulfur only for camelina cultivation on soils poor in sulfur. Afshar et al. [31] confirmed that nitrogen fertilization reduced oil content in seeds, but increased fat yield, which was an important criterion. Kumari et al. [37] showed that foliar application of boron resulted in a higher camelina seed yield as compared to the control. Combined application of boron and nitrogen also provided favorable results due to the increased fat content in seeds. Afshar et al. [31] argued that research in the field of camelina agriculture practices should be multi-faceted, which would allow for improved production results.

Magnesium content in the seeds was significantly higher after the combined application of magnesium sulfate with Plonvit R (G) compared to the sole application of urea (B). The highest iron content was obtained after a combined foliar application of magnesium sulfate with Plonvit R (G). Significantly less of the discussed element was found in seeds obtained from the control and in plots with foliar fertilization with magnesium sulfate or urea. Foliar fertilization did not modify the content of manganese, copper, and zinc in seeds. However, it was shown that the content of these microelements varied in the years of research, as shown in Table 5.

Jakubus and Bakinowska [56] obtained at high nitrogen doses (170 kg·ha^{-1}) a significantly higher uptake of all analyzed nutrients by plants compared to lower doses. Toncea et al. [52] reported that camelina seeds contained 4.25–5.24% ash, 0.18% calcium (Ca), 0.53% phosphorus (P), 0.49% copper (Cu), 1.39% manganese (Mn), 4.47% iron (Fe), and 2.56% zinc (Zn). They added that the chemical composition of seeds was modified by weather conditions in the study years. According to Zubr [57], camelina seeds contained 1.0% calcium (Ca), 0.51% magnesium (Mg), 0.06% sodium (Na), 1.6% potassium (K), 0.04% chlorine (Cl), 1.4% phosphorus (P), 0.24% sulfur (S), 329 µg/g iron (Fe), 9.9 µg/g copper (Cu), 40 µg/g manganese (Mn), 1.9 µg/g nickel (Ni), and 69 µg/g zinc (Zn). Czarnik et al. [20] showed that a higher nitrogen dose significantly increased Fe and Zn contents in seeds compared to the control.

Table 5. The content of magnesium and selected microelements in seeds.

Variant [1]	**Mg**	**Fe**	**Mn**	**Cu**	**Zn**
	g kg^{-1} DM	**mg kg^{-1} DM**			
		Foliar fertilization (F)			
A	2.56 ^{ab}	66.3 ^{c}	18.6	5.23	32.5
B	2.46 ^{b}	68.4 ^{bc}	19.3	5.36	34.6
C	2.62 ^{ab}	68.6 ^{bc}	18.8	5.22	32.7
D	2.59 ^{ab}	69.2 ^{ab}	19.6	5.37	34.8
E	2.57 ^{ab}	70.6 ^{abc}	18.9	5.20	32.3
F	2.58 ^{ab}	72.6 ^{ab}	19.8	5.37	34.9
G	2.65 ^{a}	73.6 ^{a}	19.5	5.35	33.5
H	2.60 ^{ab}	71.8 ^{ab}	19.7	5.36	33.9
		Year			
2016	2.57	67.9 ^{c}	18.6 ^{b}	4.66 ^{b}	31.8 ^{b}
2017	2.61	72.4 ^{a}	20.1 ^{a}	5.63 ^{a}	37.6 ^{a}
2018	2.55	70.1 ^{b}	19.1 ^{ab}	5.62 ^{a}	31.6 ^{b}
		Mean			
2016–2018	2.58	70.1	19.3	5.3	33.7
		ANOVA			
F	*	***	n.s.	n.s.	n.s.
Y	n.s.	***	**	***	***
FxY	n.s.	n.s.	n.s.	n.s.	n.s.

[1]—see Table 1, ***, **, * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$, n.s.—non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters (a, b, c) in columns are statistically different for foliar fertilization.

3.5. Statistical Dependencies

The statistical calculations presented in the diagram shows that fertilization with urea and urea in combination with other foliar fertilizers resulted in a similar effect. The use of foliar preparations in the variant without urea was similar to the control, especially for the fertilization with magnesium sulfate, as shown in Figure 4.

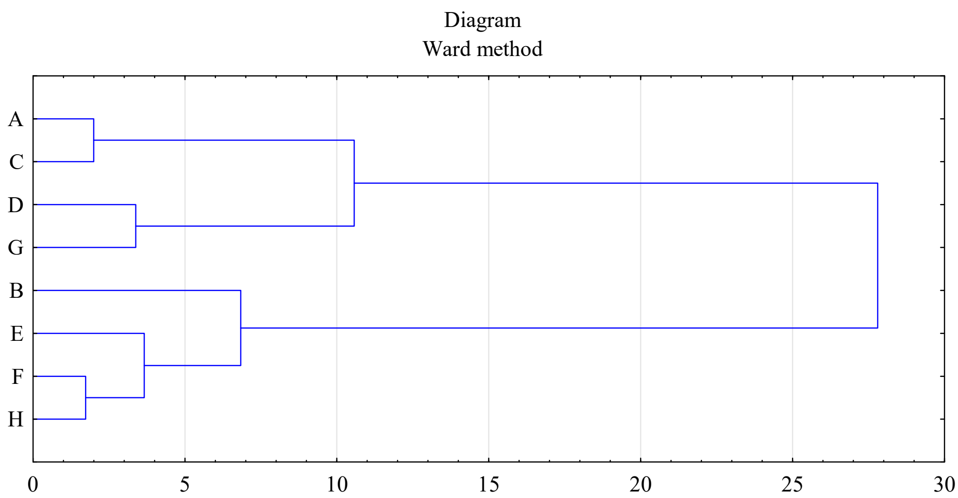

Figure 4. Dendrogram of foliar fertilization variants. Description in Table 1.

It was shown that the SPAD index was strongly positively correlated with the number of siliquae per plant and fat yield. Seed yield was strongly positively correlated with the number of siliquae per plant, TSW, fat, and protein yield. On the other hand, TSW was strongly positively correlated with protein and fat yield, as shown in Table 6.

Table 6. Correlation between selected measurements.

Measurement	LAI	SPAD	Fat Yield	Protein Yield	Seed Yield	TSW	Number of Seeds	Number of Pods
Number of pods	0.70	0.90	0.91	0.85	0.90	0.21	−0.09	1.00
Number of seeds	0.24	0.04	0.24	0.25	0.23	0.36	1.00	
TSW	0.83	0.84	0.97	0.99	0.98	1.00		
Seed yield	0.83	0.89	0.99	0.99	1.00			
Protein yield	0.84	0.87	0.98	1.00				
Fat yield	0.82	0.91	1.00					
SPAD	0.36	1.00						
LAI	1.00							

3.6. Economic Effects

The application of a combination of three fertilizers (urea, magnesium sulfate and Plonvit R) was found to be economically justified. The remaining fertilization variants were less effective than expected. This was especially true of magnesium sulfate or Plonvit R application, as shown in Table 7.

Table 7. Profitability of foliar fertilization, according to 2019 prices.

Variant [1]	Yield Increase ($t \cdot ha^{-1}$)	Yield Increase (EUR/ha)	Cost of Foliar Fertilization (EUR/ha)	Profitability (EUR/ha)
	a	b	c	d = b − c
A	-	-	-	-
B	0.22	153.49	24.65	128.84
C	0.06	41.86	10.47	31.39
D	0.05	34.88	9.30	25.58
E	0.35	244.18	30.47	213.71
F	0.45	313.95	29.30	284.65
G	0.15	104.65	15.12	89.53
H	0.53	369.77	35.12	334.65

[1]—see Table 1. Lowercase letters a, b, c, d represent the columns

Schillinger [58] stated that camelina was not stable in terms of agriculture or economy when it comes to the cultivation of older varieties in unfavorable environmental conditions and low-cost agriculture treatments. Dangol et al. [59] believed that demand for camelina oil will be determined by demand for biofuel and competitiveness on the market of other biofuels. Mohammad et al. [60] has concluded that camelina is a prospective crop, intended for biofuel. The profitability of such production is additionally increased by by-product utilization, e.g., meal or glycerin. Stolarski et al. [61] showed that the consumption of fertilizers was dominant among energy and economic inputs in camelina production. They reported that the revenue from the sale of camelina seeds averaged 312 EUR ha^{-1}, while the income from the total production of camelina biomass was on average 432.6 EUR ha^{-1}.

Certainly, not even in the rosiest future will camelina ever replace oilseed rape or sunflower, but hopefully it will become an interesting alternative to be included in European agricultural systems [62].

4. Conclusions

Weather conditions were variable in the study years, but they did not modify camelina yield. The combined use of urea, magnesium sulfate, and Plonvit R increased seed yield by 0.54 t ha^{-1} compared to the control. The remaining combinations of foliar fertilization did not bring the expected results. The average camelina yield was 1.66 t ha^{-1}. The use of three foliar fertilizers in one application was economically justified. It resulted in an increase in the SPAD and LAI index, TSW, and the yield of fat and protein. The highest number of siliquae on the plant was obtained after applying urea or urea combined with other foliar fertilizers. Urea application reduced crude fat content in seeds. Magnesium content in seeds was significantly higher after the combined application of magnesium sulfate with Plonvit R compared to urea application alone. The highest iron content was obtained after foliar application of magnesium sulfate with Plonvit R. Significantly lower levels of this element were determined in seeds obtained from the control and plots with magnesium sulfate or urea foliar fertilization. In the cultivation of spring camelina, a multi-component foliar fertilization can be recommended.

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