

Article

The Reaction of Winter Oilseed Rape to Different Foliar Fertilization with Macro- and Micronutrients

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Abstract: Foliar fertilization provides cultivated plants with the necessary nutrients during the growing season. The conducted field experiment was aimed at comparing the effectiveness of different variants of foliar fertilization applied in the cultivation of winter oilseed rape (*Brassica napus* L.), cultivar 'ES Cesario'. The experimental factors were: A (control), B (YaraVita Brassitrel Pro), C (YaraVita Brassitrel Pro and YaraVita Thiotrac), D (YaraVita Brassitrel Pro and YaraVita Bortrac), E (YaraVita Brassitrel Pro and YaraVita Bortrac and YaraVita Thiotrac) and F (YaraVita Thiotrac). Weather conditions were variable over the years of the study and had a modifying effect on most of the tested parameters. Intensive foliar fertilization (variants D and E) resulted in a significant increase in the number of pods per plant, seed and fat yields, and SPAD (soil plant analysis development) and LAI (leaf area index) indices compared to the control. The protein yield was the highest after fertilizer applications in variants C and E. The use of YaraVita Thiotrac alone (variant F) did not provide the expected results. Foliar fertilizers applied in variant D increased Gs (leaf stomatal conductance) measurements and fat content in seeds but decreased TSW and seed protein content. It was shown that intensive foliar fertilization (variants D and E) increased seed boron content compared to YaraVita Thiotrac fertilization and the control. Fat and protein yields were strongly positively correlated with seed yield ($r = 0.93$ and $r = 0.71$, respectively). The best economic effect was obtained after applying foliar fertilization in variants D and E; therefore, they can be recommended for agricultural practice.



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Keywords: *Brassica napus* L.; foliar fertilization; nutrients; yield components; yield; seed quality

1. Introduction

Winter oilseed rape is an important oil plant in Europe, grown mainly for edible oil and biofuel. In the European Union, the highest oilseed rape yields are recorded in France, Germany and Poland. Pullens et al. [1] argued that oilseed rape production could shift northwards due to the changing climate. Ahmadi et al. [2] have pointed out, however, that this species is sensitive to an unfavorable pattern of environmental conditions. Therefore, various types of stress disrupt the growth and development of oilseed rape plants. Wenda-Piesik and Hoppe [3] showed that the use of high-input technology in the cultivation of oilseed rape increased the winter hardiness of plants, number of pods per plant, number of seeds per pod and seed yield. The latter authors considered the optimization of mineral fertilization to be particularly important among the elements of agriculture practices. Fageria et al. [4] have confirmed that both soil and foliar fertilization is necessary in oilseed rape cultivation. They also pointed out that if foliar fertilization was combined with herbicide, insecticide or fungicide application, the cost of the treatment would be reduced. Ossewaarde and Ossewaarde-Lowtoo [5] have noted that the introduction of the European Green Deal forces changes in the approach to plant production, which should become more environmentally friendly. In the studies by Ganya et al. [6] and Amiri et al. [7], the response of oilseed rape plants to the applied foliar fertilizers varied, which resulted in differences in the obtained seed yield compared to control. Rios et al. [8] have concluded that foliar fertilization is now a commonly applied treatment, and new preparations are continuously

introduced into agricultural practice, also thanks to nanotechnology. Shahsavari et al. [9] showed that the yield of winter oilseed rape significantly increased after the applied fertilization, especially during water stress. Beres et al. [10] proved that winter oilseed rape required fertilization already during autumn vegetation. It affected the condition of the plants and hardened them before winter. In this aspect, Poisson et al. [11] added that modern agriculture should strive to reduce the doses of soil fertilizers while retaining high and good quality yields. This is dictated by a compromise between environmental and economic goals. Gonzalez et al. [12] indicated that these requirements were met especially by foliar fertilizers. Therefore, soil fertilizers should be supplemented with foliar fertilizers, and their doses and dates should be precisely defined. Siede et al. [13] presented interesting research results, which showed that the foliar application of boron did not threaten bees. This is of practical and environmental importance. Lemaire et al. [14] emphasized that currently, nondestructive leaf diagnostic methods are used. This allows for determining crop fertilization needs, mainly for nitrogen. This is an important aspect in modern precision agriculture that uses remote sensing methods to monitor crops [15]. Kwiatkowski [16] proved that foliar fertilization of winter oilseed rape in autumn resulted in improved winter hardiness of plants and increased yield. At the same time, it allowed for reducing the dose of NPK mineral fertilizers by 25%. Jankowski et al. [17] obtained a higher seed yield by $0.25 \text{ t}\cdot\text{ha}^{-1}$ as compared to a control, as a result of autumn foliar fertilization. Additionally, crude fat content in seeds significantly increased from 1.3 to $7.4 \text{ g kg}^{-1} \text{ dw}$, depending on the variant used. Jarecki et al. [18] obtained the best results after multiple application of foliar fertilizers (in autumn and spring or twice in spring) in comparison to a control. They achieved much smaller effects when they performed a one-time spraying only in the autumn or only in the spring. White et al. [19] showed that additional fertilization of 40 kg of nitrogen per hectare at the end of flowering significantly increased the yield of winter oilseed rape seeds. The obtained increase in the yield ranged from 0 to $0.41 \text{ t}\cdot\text{ha}^{-1}$, depending on the location of the experiment. Sikorska et al. [20] indicated that foliar fertilization with sulfur and boron in combination with biostimulants was most effective on yield components and yield of winter oilseed rape. In turn, Froese et al. [21] pointed out an important role of phosphorus in the fertilization of crops. However, foliar application of this element had little effect on the yield and quality of winter oilseed rape seeds. Kováčik et al. [22] drew attention to the possibility of fertilizing winter oilseed rape with titanium. They showed that the uptake of this element by plants was about 18 g per one ton of seeds, including straw. Jankowski et al. [23] reported that intensive foliar fertilization of oilseed rape increased seed yield ($0.43\text{--}0.69 \text{ t}\cdot\text{ha}^{-1}$) and straw yield ($0.59\text{--}1.69 \text{ t}\cdot\text{ha}^{-1}$) and modified seed quality, not always favorably. Gugala et al. [24] indicated that some applied variants of foliar fertilization increased the content of glucosinolates in seeds.

The aim of the experiment was to evaluate the effect of five variants of foliar fertilization on the yield and quality of winter oilseed rape seeds. The economic effects of the performed treatments were presented at the final stage of the research in comparison to the control. 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. Experimental Design

The field experiment was carried out in the 2017/2018, 2018/2019 and 2019/2020 seasons in the fields of the Experimental Station for Variety Testing in Przecław ($50^{\circ}11' \text{ N}$, $21^{\circ}29' \text{ E}$, altitude 185 m a.s.l.), southeastern Poland. The experiment was set up in four replicates in a random block design. The tested factor was the differentiated foliar fertilization of winter oilseed rape, cv. ES Cesario, as shown in Table 1.

Table 1. Applied variants of foliar fertilization.

Date (Scale BBCH)	Variant of Foliar Fertilization per 1 ha					
	A Control	B	C	D	E	F
BBCH 14		YaraVita Brassitrel Pro—1 L	YaraVita Brassitrel Pro—1 L	YaraVita Brassitrel Pro—1 L + YaraVita Bortrac—1 L	YaraVita Brassitrel Pro—1 L + YaraVita Bortrac—1 L	
BBCH 18		YaraVita Brassitrel Pro—1 L	YaraVita Brassitrel Pro—1 L	YaraVita Brassitrel Pro—1 L + YaraVita Bortrac—1 L	YaraVita Brassitrel Pro—1 L + YaraVita Bortrac—1 L	
BBCH 30		YaraVita Brassitrel Pro—4 L	YaraVita Brassitrel Pro—4 L	YaraVita Brassitrel Pro—4 L + YaraVita Bortrac—1 L	YaraVita Brassitrel Pro—4 L + YaraVita Bortrac—1 L	
BBCH 59				YaraVita Bortrac—1 L	YaraVita Bortrac—1 L	
BBCH 68			YaraVita Thiotrac—5 L		YaraVita Thiotrac—5 L	YaraVita Thiotrac—5 L

The following experimental factors were selected for foliar fertilization:

- YaraVita Brassitrel Pro containing (g/L): 69 N, 118 MgO, 125 CaO, 60 B, 70 Mn, 4 Mo;
- YaraVita Bortrac containing (g/L): 150 B;
- YaraVita Thiotrac containing (g/L): 200 N, 750 SO₃.

For soil and foliar fertilization, fertilizers from Yara Poland Sp. Z o.o. were used. The following solid fertilizers (Table 2) were applied for the entire experiment:

- YaraMila RAPS containing (%): 16 N, 8 P₂O₅, 16 K₂O, 1.7 MgO, 12.5 SO₃, 0.1 B;
- YaraBela SULFAN containing (%): 24 N, 10.5 CaO, 1.5 MgO, 16.2 SO₃.

Table 2. Solid fertilizers used for the entire field experiment.

Date (Scale BBCH)	Solid Fertilizer Dose
before sowing	YaraMila RAPS—200 kg
BBCH 20	YaraMila RAPS—600 kg
BBCH 51	YaraBela SULFAN—300 kg

The total dose of all nutrients, as a result of the applied fertilization, was (kg·ha⁻¹) as follows:

Variant A: 200 N, 64 P₂O₅, 128 K₂O, 31,5 CaO, 18.1 MgO, 148.6 SO₃, 0.8 B;

Variant B: 200,41 N, 64 P₂O₅, 128 K₂O, 32,25 CaO, 18.81 MgO, 148.6 SO₃, 1.16 B, 0.42 Mn, 0.024 Mo;

Variant C: 201.41 N, 64 P₂O₅, 128 K₂O, 32,25 CaO, 18.81 MgO, 152.35 SO₃, 1.16 B, 0.42 Mn, 0.024 Mo;

Variant D: 200,41 N, 64 P₂O₅, 128 K₂O, 32,25 CaO, 18.81 MgO, 148.6 SO₃, 1.76 B, 0.42 Mn, 0.024 Mo;

Variant E: 201,41 N, 64 P₂O₅, 128 K₂O, 32,25 CaO, 18.81 MgO, 152.35 SO₃, 1.76 B, 0.42 Mn, 0.024 Mo;

Variant F: 1 N, 3.75 SO₃.

The experiment was carried out using the cultivar ES Cesario (Euralis Nasiona Ltd., Poznań, Poland). It is a hybrid with high winter hardiness and high yield obtained in the research area.

2.2. Soil Conditions

The experiment was located in soil originated from clay loam classified as Fluvic Cambisol (CMfv), according to [25]. In 2019, the pH of the soil was slightly acidic, while it was neutral in 2017 and 2018. The soil was characterized by an average content of

phosphorus and potassium, high content of magnesium and low content of sulfur. In all years of research, the content of zinc, copper, iron and manganese was moderate, while the content of boron was low, as shown in Table 3.

Table 3. Chemical properties of soil at the depth of 0–60 cm.

Measurement	2017	2018	2019
pH in KCl	6.9	7.2	6.1
N _{min} kg·ha ⁻¹	51.3	53.4	62.6
Humus %	1.8	1.7	2.1
Content of available nutrients			
P ₂ O ₅	11.4	14.9	10.2
K ₂ O	16.5	20.0	14.5
Mg	7.2	8.8	8.1
S-SO ₄	1.6	1.8	1.9
B	1.4	1.8	1.2
Zn	15.7	16.4	14.6
Cu	3.5	3.8	4.2
Fe	2856	1963	2267
Mn	195.3	235.6	256.3

2.3. Field Conditions

The area of a single plot was 15 m², and the isolation strips were 1.5 m. The sowing rate was 50 seeds per m², row spacing was 25 cm and sowing depth was 1.5 cm. Winter wheat was the forecrop. The seeds were sown on 24 August 2017, 23 August 2018 and 27 August 2019. The agriculture treatments were performed in accordance with the methodology of the Research Centre for Cultivar Testing (COBORU) in Słupia Wielka, Poland. Weeds, diseases and pests were controlled throughout the growing season by applying plant protection products. Chemical spraying was performed with a tractor sprayer in accordance with the instructions on the labels. Foliar fertilizers were applied separately with a manual sprayer with a capacity of 10 l. Oilseed rape was harvested at full seed maturity with a plot harvester (Wintersteiger Classic). Seed yield from the plot was calculated per 1 ha at 9% constant moisture.

2.4. Field Measurements

The measurement of stomatal conductance of the leaves (Gs) was performed with a Porometer SC-1 apparatus (METER Group, Inc., Pullman, USA). Soil plant analysis development (SPAD) was measured with a SPAD 502P meter (Konica Minolta, Inc., Tokyo, Japan). Gs and SPAD measurements were performed on 30 oilseed rape leaves. Leaf area index (LAI) measurements were performed using an AccuPAR LP-80 instrument (METER Group, Inc., Pullman, WA, USA). Plant development stages were given according to the BBCH scale—Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [26]. Gs, SPAD and LAI measurements were performed at the BBCH 69 phase in the morning.

2.5. Laboratory Measurements

The number of plants per 1 m² was counted before harvesting. For biometric measurements, 20 plants were collected from each plot in order to determine the number of pods per plant, number of seeds in the pod and thousand seed weight (moisture—9%).

The content of total protein and crude fat in the seeds was determined by near infrared spectroscopy (NIRS) using an MPA FT NIR spectrometer (Bruker, Billerica, MA, USA). Protein and fat yields per ha were calculated based on seed yield and the percentage of a given component in seeds.

In order to determine certain macro- and micronutrients, seed samples were mineralized in a mixture of concentrated HNO₃ acids: HClO₄:H₂SO₄ in a ratio of 20:5:1, in an open system in a Tecator heating block. The content of Ca, Mg and Mn in the obtained

samples was determined by atomic absorption spectroscopy (FAAS) using a Hitachi Z-2000 apparatus (Tokyo, Japan). Boron content was determined by the colorimetric method using a Shimadzu UV-1201V spectrophotometer (Kyoto, Japan).

2.6. Economic Analyses

Prices for economic calculations are given for 2020. Exchange rate: 1 EUR = 4.48 PLN. The purchase price for winter rapeseed seeds was 379.46 EUR per ton. Costs of foliar fertilizers are given in accordance with the offer of the selling companies (YaraVita Brassitrel Pro 4.22 PLN/L, YaraVita Bortrac 2.57 PLN/L, YaraVita Thiotrac 1.96 PLN/L) and calculated per 1 ha. Cost of foliar spraying—11.16 EUR per 1 ha.

2.7. Statistical Analyses

The results of the study were statistically analyzed using analysis of variance (ANOVA), implemented in Statistica 13.3.0 (TIBCO Software Inc., Palo Alto, CA, USA). Significance of differences between treatments was verified by the Tukey test.

3. Results

3.1. Weather Conditions

The weather conditions varied during the years of the study (Figures 1 and 2). Rainfall in autumn was sufficient for normal plant growth. Air temperatures in the autumn of 2017 were similar to multiannual data and higher in 2018 and 2019. During the winter rest period, January was the coldest month in 2019 and 2020, and February in 2018. In spring, low precipitation was recorded in April 2018 and June 2019. It was rainy in May in 2019 and 2020. Low air temperatures compared to multiannual data were recorded in March 2018 and April and May 2020. June 2019 was exceptionally warm. In July 2018, heavy rainfall made seed harvesting difficult.

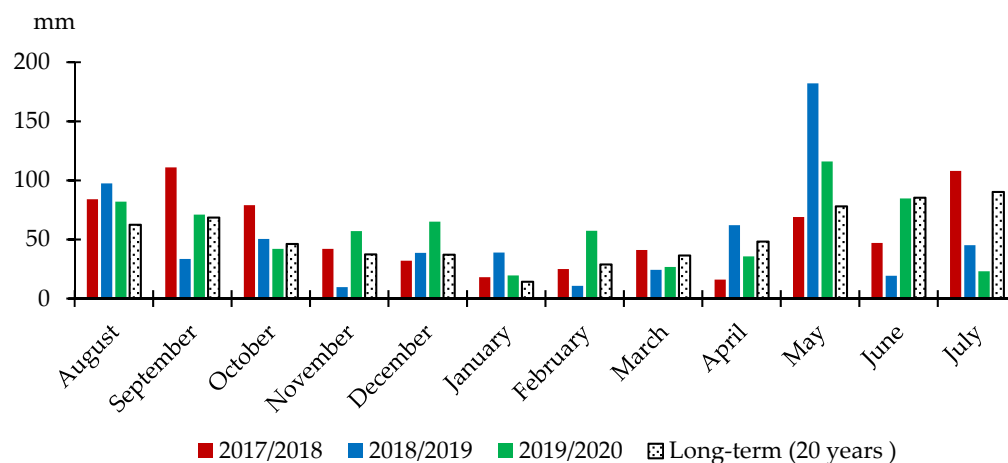


Figure 1. Mean monthly rainfall.

3.2. Results of Field and Biometric Measurements

Foliar fertilization had no effect on plant density before harvesting. On the other hand, the studied trait varied during the study years. In 2018, canopy density was the highest, while it was significantly lower in 2019 and 2020. The applied intensive foliar fertilization in variants D and E resulted in a significant increase in the number of pods per plant. The lowest result for the discussed parameter was obtained in the control plants. In 2020, the number of pods per plant was higher by 68.5 plants compared to 2018. This could be the result of different plant densities per unit area. The number of seeds in the pod was on average 22.6 and did not depend on foliar fertilization. In 2020, there were significantly more seeds in the pod compared to 2018 and 2019. It was shown that after the application of foliar fertilizers in variant D, TSW decreased compared to the control and fertilization

variants B and E. The least robust seeds were obtained in 2020 (Table 4). With respect to TSW, a significant interaction of fertilization with the years of research was noted (Table S1). The highest TSW, 7.6 g, was obtained in 2019 after foliar spraying in variants C and E. The lowest TSW, 4.5 g, was recorded in 2020 after application of foliar fertilizers in variant C.

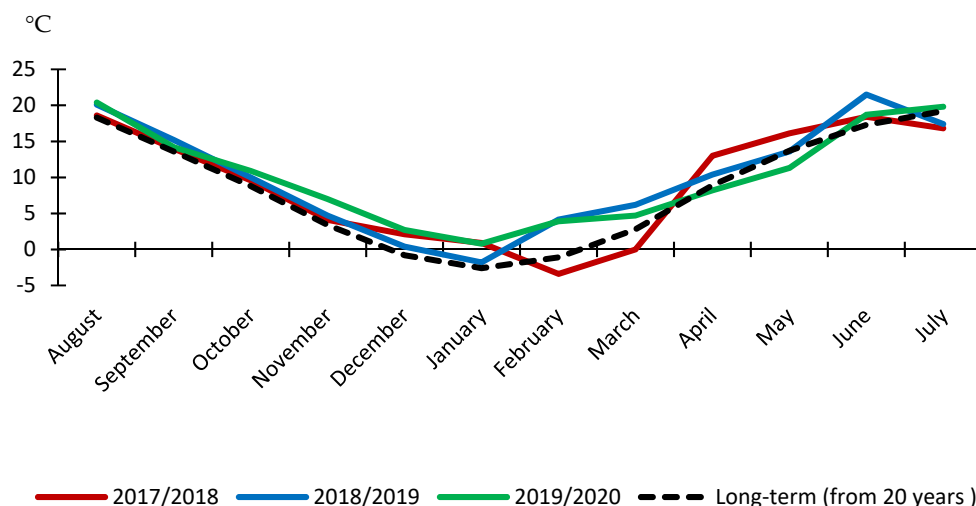


Figure 2. Mean monthly air temperature.

Table 4. 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	34.6	93.5 ^c	21.9	6.37	4.26
B	32.8	105.6 ^b	22.9	6.33	4.58
C	36.7	102.6 ^b	22.9	6.15	4.73
D	34.3	110.4 ^a	23.2	5.90	4.81
E	32.0	112.3 ^a	22.6	6.43	4.94
F	34.5	100.9 ^{bc}	22.2	6.22	4.35
Year (Y)					
2018	43.1 ^a	72.5 ^c	22.3 ^b	6.44	4.39
2019	30.3 ^b	99.1 ^b	21.8 ^b	7.31	4.68
2020	29.1 ^b	141.0 ^a	23.8 ^a	4.95	4.76
Mean					
2018–2020	34.2	104.2	22.6	6.23	4.61
ANOVA					
F	n.s.	*	n.s.	**	***
Y	***	***	***	***	***
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–c) in columns are statistically different for foliar fertilization.

A high seed yield was obtained after fertilizer application in variant E and a slightly lower yield in variant D. The use of YaraVita Thiotrac alone (variant F) did not bring the expected results compared to the control. The highest yield of oilseed rape was recorded in 2020, and the lowest in 2018. With respect to seed yield, a significant interaction of fertilization with the years of research was noted (Table S1). In 2018 and 2020, the highest seed yield was obtained after fertilizer application in variants D and E, respectively. It was

more than 5 t·ha⁻¹. The lowest yield, 3.4 t·ha⁻¹, of winter rapeseed was obtained in the control in 2018.

3.3. The Yield of Fat and Protein

The content of fat in seeds slightly varied under the influence of foliar fertilization. Higher concentration of the discussed component was determined after applying fertilization variant D compared to control.

The fat yield per hectare was the highest after the application of intensive foliar fertilization (variants D and E). A significantly lower fat yield was obtained on the plots where fertilizer variants B and C were applied. The lowest fat yield was achieved by plants fertilized only with YaraVita Thiotrac and control plants. The fat content in seeds and fat yield per hectare were the highest in 2019 and the lowest in 2018.

The protein content in the control seeds was over 20%. Significantly lower protein content was found in seeds collected from the plots where fertilization variant D was applied. The protein yield was the highest after using fertilizers in variants C and E. Significantly lower protein yield was recorded after applying fertilization variants B and F and in the control. Seed protein content and protein yield varied in the study years (Table 5). Both protein and fat contents as well as the yield of both components showed a significant interaction between fertilization and the years of the study (Table S2). The 2018/2019 season was conducive to an increase in seed fat content, especially after fertilizer applications in variants B, C, D and F. In 2018, the lowest fat content was determined in control seeds. In contrast, the protein content was the highest. In 2020, the lowest seed protein content was determined after fertilizer application in variant D. In 2017, the fat and protein yield of the control was lower significantly compared to the other study years.

Table 5. Chemical composition of seeds and yield of fat and protein.

Variant ¹	Fat Content (%)	Fat Yield (t·ha ⁻¹)	Protein Content (%)	Protein Yield (t·ha ⁻¹)
Foliar fertilization (F)				
A	47.4	2.02	20.1	0.86
B	48.0	2.20	19.1	0.87
C	47.8	2.26	19.6	0.93
D	48.4	2.34	18.8	0.90
E	47.6	2.35	19.3	0.95
F	47.9 ^{ab}	2.08 ^c	19.6	0.85
Year (Y)				
2018	46.1	2.02	20.8	0.91
2019	49.9	2.34	18.6	0.87
2020	47.5	2.26	18.8	0.89
Mean				
2018–2020	47.8	2.21	19.4	0.89
ANOVA				
F	*	***	**	***
Y	***	***	***	*
FxY	***	***	***	***

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–c) in columns are statistically different for foliar fertilization.

3.4. Field Measurements

Foliar fertilization applied in variant E significantly increased the SPAD measurements. High readings of the discussed index were also obtained in fertilization variant D. The lowest SPAD values were recorded in control plants.

Intensive foliar fertilization (variants D and E) increased the LAI measurements. A lower index reading was obtained after applying fertilizers in variants B and C. The lowest LAI readings were recorded after YaraVita Thiotrac application (variant F) and in the control.

Leaf stomatal conductance (Gs) was the highest after foliar fertilization in variant D. The lowest Gs values were obtained after using YaraVita Thiotrac and on plots with fertilization variant C. High SPAD readings were recorded in 2020 and high LAI readings in 2018 (Table 6). For LAI and Gs, significant interactions of fertilization with the years of the study were recorded (Table S3). In 2018, the LAI index was the highest after using foliar fertilization in variants D and E. However, in 2019, an inverse relationship was obtained. In 2018, the lowest Gs measurements were obtained after foliar application of fertilizers in variant F. This differs significantly from other readings obtained.

Table 6. Field measurements of SPAD, LAI and Gs indices.

Variant ¹	SPAD	LAI	Gs (mmol m ⁻² s ⁻¹)
Foliar fertilization (F)			
A	56.7 ^c	3.25	328.4
B	57.0 ^{bc}	3.45	334.5
C	57.5 ^b	3.50	277.4
D	58.3 ^{ab}	3.62	368.8
E	59.0 ^a	3.69	334.2
F	57.1 ^{bc}	3.21	265.3
Year (Y)			
2018	58.2 ^b	4.50	319.4
2019	50.3 ^c	2.37	317.7
2020	64.3 ^a	3.50	317.2
Mean			
2018–2020	57.6	3.45	318.1
ANOVA			
F	**	***	***
Y	***	***	n.s.
FxY	n.s.	**	***

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

3.5. Chemical Composition

Foliar fertilization did not modify the content of magnesium, calcium and manganese in seeds. It was only observed that intensive foliar fertilization (variants D and E) increased seed boron content compared to YaraVita Thiotrac fertilization and control. A high content of magnesium was found in seeds harvested in 2018 and 2019, while a high content of calcium was found in 2018 (Table 7).

3.6. Statistical Dependencies

Fat and protein yields were strongly positively correlated with seed yield. Moreover, fat yield was positively correlated with the content of this component in seeds and negatively correlated with seed protein content. SPAD index correlation with seed yield was positive but lower than expected. However, it was found that the LAI was positively correlated with fat yield, as shown in Table 8.

Table 7. The content of selected macro- and microelements in seeds.

Variant ¹	Mg	Ca	Mn	B
	(g·kg ⁻¹)	(g·kg ⁻¹)	(mg·kg ⁻¹)	(mg·kg ⁻¹)
Foliar fertilization (F)				
A	4.43	3.58	39.4	8.4 ^{bc}
B	4.46	3.63	41.2	8.8 ^{ab}
C	4.45	3.61	41.9	8.7 ^{ab}
D	4.47	3.61	40.6	9.2 ^a
E	4.45	3.59	40.4	9.1 ^a
F	4.42	3.57	39.5	8.2 ^c
Year				
2018	4.58 ^a	3.82 ^a	40.8	8.9
2019	4.54 ^a	3.51 ^b	39.6	8.6
2020	4.22 ^b	3.47 ^b	41.1	8.7
Mean				
2018–2020	4.45	3.60	40.5	8.7
ANOVA				
F	n.s.	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 $p < 0.001$ and $p < 0.01$, n.s.—non-significant, according to Tukey's honestly significant difference (HSD) test. Mean values with different letters (a–c) in columns are statistically different for foliar fertilization.

Table 8. Correlation coefficients between selected measurements.

Specification	Seed Yield (t·ha ⁻¹)	Fat Yield (t·ha ⁻¹)	Protein Yield (t·ha ⁻¹)
Seed yield (t·ha ⁻¹)	1.00	0.93 *	0.71 *
Fat yield (t·ha ⁻¹)	0.93 *	1.00	0.48 *
Protein yield (t·ha ⁻¹)	0.71 *	0.48 *	1.00
Plant density (t·ha ⁻¹)	−0.27 *	−0.41 *	0.17
Number of pods	0.43 *	0.42 *	0.05
Number of seeds	0.26 *	0.16	0.15
TSW (g)	−0.12	0.04	−0.04
Fat content (%)	0.29 *	0.61 *	−0.30 *
Protein content (%)	−0.41 *	−0.63 *	0.34 *
SPAD	0.40 *	−0.19	0.14
LAI	0.30 *	0.548	−0.17
Gs	0.28 *	0.25 *	0.22

* significant differences at $p < 0.05$.

3.7. Economic Effects

The applied variants of foliar fertilization brought different economic benefits compared to the control. The most profitable was the use of intensive foliar fertilization in variants D and E. Fertilization used in variants B and C had lower effects. The application of only YaraVita Thiotrac fertilizers was the least profitable (Table 9). It should be noted that the increase in yield obtained in variant F was statistically insignificant compared to the control.

Table 9. Profitability of foliar fertilization, according to 2020 prices.

Variant ¹	Yield Increase (t·ha ⁻¹)	Yield Increase (EUR·ha ⁻¹)	Cost of Foliar Fertilization (EUR·ha ⁻¹)	Profitability (EUR·ha ⁻¹)
A	-	-	-	-
B	0.32	121.43	58.80	62.63
C	0.47	178.35	79.76	98.59
D	0.55	208.70	80.24	128.46
E	0.68	258.03	101.2	156.83
F	0.09	34.15	20.96	13.19

¹ see Table 1.

4. Discussion

The results showed the different effectiveness of the applied foliar fertilization variants. On average, in the years of research, the highest increase in the seed yield was obtained after intensive fertilization (variants D and E). The obtained difference was 0.55 and 0.68 t·ha⁻¹ higher compared to the control, respectively, i.e., nearly 13 and 16% (Table 8). A one-time application of only YaraVita Thiotrac did not bring about the expected result. Zhivko and Radka [27] also confirmed the effectiveness of foliar fertilizers in winter oilseed rape agriculture practices and high yield variability in the study years. The best foliar fertilization variant allowed the authors to obtain an increase in seed yield from 7 to 11% compared to the control. Ali et al. [28], as a result of the conducted experiment, determined optimal concentration of foliar fertilizer to be used in winter oilseed rape cultivation. Such results allowed for obtaining satisfactory yield-enhancing effects in agricultural practice. Heuermann et al. [29] indicated that soil fertilization of oilseed rape with ammonium nitrate had a positive effect on the increase of seed yield compared to urea; however, it was not statistically unequivocally proven due to the influence of seasonal fluctuations. Sikorska et al. [30] achieved the highest increase in thousand seed weight and seed yield after the application of compound fertilizers containing sulfur, boron and amino acids. Kwiatkowski [16] demonstrated that the best combination of fertilization for oilseed rape was 75% of the NPK dose and additional autumn spraying with urea + nickel chelate + magnesium sulfate. This combination allowed for reducing the dose of soil fertilizers and simultaneously obtaining a high and good quality seed yield. Jankowski et al. [31] reported that only boron foliar fertilization of oilseed rape at the beginning of budding phase increased seed yield from 0.19 t·ha⁻¹ (3%) to 0.26 t·ha⁻¹ (4%), depending on the tested variant. The recorded increase in seed yield in response to foliar boron application was attributed to the effect of this micronutrient on seed setting in pods. Ni and Punja [32] added that the increased boron content in oilseed rape leaves reduced *Sclerotinia sclerotiorum* development. Hence, they considered it justified to conduct multifaceted research in the field of foliar fertilization, including the possibility of limiting crop disease development.

In the current experiment, the yield of winter oilseed rape and most of the assessed traits and parameters were significantly modified in the study years. The obtained difference in seed yield between 2018 and 2020 was 0.37 t·ha⁻¹. Additionally, interactions between the fertilization and years were demonstrated with respect to seed, fat and protein yields. Száková et al. [33] reported that soil and climate conditions influenced selenium uptake by oilseed rape. They obtained higher selenium content in plants grown in acidic soil, especially in years with higher total rainfall. They also indicated the need to optimize Se fertilization in specific soil and climatic conditions in order to obtain the maximum effect of biofortification. Sikorska et al. [20] showed that different weather conditions in the study years modified yield components of the assessed cultivars of winter oilseed rape. In another experiment, Sikorska et al. [30] found that climatic conditions in the research years significantly modified thousand seed weight and yielding of winter oilseed rape. This was confirmed in the present study, as shown in Table 3. Malhi et al. [34] concluded that oilseed rape did not always respond to boron foliar fertilization with increased seed yield, especially under field conditions. However, it depended on many factors, including type

of fertilizer, forecrop, year or cultivar. Koohkan et al. [35] showed that in the case of excess boron, its toxicity to oilseed rape could be reduced by nitrogen fertilization. Brennan and Bolland [36], using foliar fertilization with boron (Borax–11% B), alone or in combination with molybdenum and/or manganese, did not achieve a significant increase in the yield of winter oilseed rape seeds. Furthermore, none of the applied fertilization variants had any influence on the fat content in seeds. In turn, Ma et al. [37] reported that oilseed rape showed a high demand for boron. Foliar application of this microelement during the flowering phase was more effective compared to soil fertilization. Malhi and Gill [38] believed that high nitrogen doses could induce sulfur deficiency symptoms in oilseed rape plants. In such cases, the application of sulfur increased the yield and fat content in seeds. Lucas et al. [39], after applying nitrogen and sulfur fertilization, achieved high yield of oilseed rape, while fat and protein contents in seeds was not modified. Ma et al. [40] also showed that sulfur fertilization was justified at high nitrogen doses. However, fertilization with boron did not provide the expected results. Therefore, Sikorska et al. [41] have rightly noticed that foliar fertilization is a frequently used treatment in winter oilseed rape, but further studies are needed to assess the effectiveness of foliar fertilization on various cultivars and in changing environmental conditions. Puzyńska et al. [42] added that individual winter oilseed rape cultivars were characterized by different yields (cultivars Nelson and Digger), and additionally, they could react differently to foliar fertilization. The results of the study by Mahdi et al. [43] demonstrated that oilseed rape responded favorably to nanofertilizers. Iron applied in such a fertilizer had the most beneficial effect on most of the assessed traits of winter oilseed rape.

In the current work, one-component (YaraVita Bortrac), two-component (YaraVita Thiotrac) and multicomponent (YaraVita Brassitrel Pro) fertilizers were applied. Depending on the variant, different components were applied at different time periods, which allowed for assessing their impact on the size and quality of oilseed rape yield. It was shown that foliar fertilization modified the content of fat and protein in seeds (Table 4) and only of boron from mineral components (Table 6). Varga et al. [44] indicated that the yield of winter oilseed rape varied between years. The effectiveness of foliar fertilizers was also modified by weather conditions, as demonstrated in long-term studies. Kováčik et al. [22] used Mg and Ti and obtained an increase in the yield of winter oilseed rape seeds from 0.3 to 0.63 t·ha⁻¹ compared to a control. Oilseed rape yielded higher after three applications of Mg and Ti compared to two applications. Yang et al. [45] increased oilseed rape seed yield by 46.1% after soil fertilization with boron compared to a control. The application of fertilizers containing molybdenum and zinc had a much smaller effect. The effect of boron on seed yield was due to the increased seed number in a pod and the number of pods per plant. Combined B with Mo fertilization or B with Zn resulted in a higher seed yield than applying B, Mo or Zn alone. In turn, seed yield after B + Mo + Zn application was the highest and amounted to 68.1% compared to control. Jankowski et al. [17] indicated that the overwintering of winter oilseed rape improved by 8–11% after two-time foliar fertilization at the BBCH 14 and 16 stages. The effect was negligible in the case of a single spraying. Gugała et al. [46] confirmed that foliar fertilization with sulfur and boron in combination with amino acids increased the number of rosette leaves (on average by 27.1%), root neck diameter (on average by 11.0%) and root length (on average by 9.7%) and ensured better wintering of the plant compared to a control. Jankowski et al. [31] showed that foliar boron fertilization increased the content of this element in oilseed rape seeds but decreased Zn and Fe contents. Overall, they showed that a foliar fertilizer containing boron improved the nutritional value of the seeds but worsened their forage value. White et al. [19] reported that foliar application of nitrogen decreased fat content in seeds by 11 g·kg⁻¹ but increased protein content by 11 g·kg⁻¹. In the experiment of Kováčik et al. [22], fat yield per hectare increased with Mg and Ti treatment compared to a control, regardless of the dose and date of foliar fertilization used. Jarecki et al. [18] showed that protein and fat yields reached the highest values when foliar fertilization was applied in the following periods: autumn + spring, autumn + twice in spring or twice in spring. Other tested options did

not bring about the expected results. Stepien et al. [47] obtained the highest fat yield of winter oilseed rape in the high-input technology and crop rotation, and the lowest in the low-input technology and cultivation in monoculture. Jankowski et al. [17] recorded the highest content of macronutrients in the above-ground parts (N, K, Mg) and roots (K) of winter oilseed rape in autumn after two-time foliar fertilization. On the other hand, the level of micronutrients (Cu, Mn, Fe) in the roots increased after a single autumn spraying. Jarecki et al. [18] found that foliar fertilization in the period of autumn + twice in spring or twice in spring increased protein and Mg contents in seeds. Barczak et al. [48] obtained a higher fat content in seeds and higher yield after soil fertilization with sulfur compared to foliar application. They noted the beneficial effect of sulfur on important quality traits of spring oilseed rape when applied both individually and in combination with nitrogen. Sienkiewicz-Cholewa and Kieloch [49] showed that fertilization of winter oilseed rape with sulfur, boron and copper resulted in an increase in the content of these elements in plants as well as the size and quality of seed yield.

Various methods are used to diagnose plants during vegetation: visual, chemical analyses or field measuring devices. In the present study, the following measurements were applied: the SPAD coefficient and the LAI and Gs indices, as presented in Table 6. This allowed for obtaining quick and nondestructive results regarding the condition of plants during the growing season. Jarecki et al. [18] showed that foliar fertilization in autumn + spring, autumn + twice in spring and twice in spring increased the SPAD values compared to control plants. The application of foliar fertilizers in autumn + spring or autumn + twice in spring resulted in an increase in the LAI value. Pużyńska [42] proved that S and B fertilization modified the SPAD index. She obtained higher measurements for each cultivar in the flowering phase after nitrogen fertilization compared to a control. Kováčik et al. [50] reported that the application of Mg-Tytanit in the BBCH 50–52 and BBCH 59 growth phases increased chlorophyll a and b contents. The increase in the content of chlorophyll b was more significant than of chlorophyll a. However, the third spraying with Mg-Tytanit (BBCH 66–67) reduced the total chlorophyll content. In another experiment, Kováčik et al. [22] showed that the Mg-Tytanit biostimulant increased the phytomass of winter oilseed rape, regardless of the dose and application period. The effect of Mg-Tytanit preparation on the content of total chlorophyll depended on application date. A beneficial effect was only found when the application was performed at the BBCH 59 phase. Zhivko [51] did not confirm the influence of the applied fertilization variants on the stomatal conductance index (Gs). However, other physiological plant measurements allowed this author to indicate the most effective fertilizer. Dunn and Goad [52] concluded that noninvasive measurements on leaves allowed for obtaining important information about the plants' health status, on the condition, however, that they are performed with precision, especially in the field. Liu et al. [53] have shown a great potential of remote sensing and images obtained in crop monitoring and diagnostics. This allows for precise determination of fertilization requirements during the growing season, especially with nitrogen.

The intensive foliar fertilization used in our experiment (variants D and E) was profitable despite higher costs (Table 8). It resulted from the obtained higher yield as compared to the control. The application of only YaraVita Thiotrac did not provide the expected results, but it was justified in combination with other fertilizers. Groth et al. [54] showed that the economic and energy efficiency of oilseed rape cultivation was the highest in case of hybrid cultivation, followed by semidwarf cultivar and population cultivar. Cultivation of the hybrid cultivar provided the highest revenues in the technology of 230 kg N ha⁻¹ and 40 kg N ha⁻¹, and the highest income in the technology of 130 kg N ha⁻¹ and 40 kg N ha⁻¹. Therefore, it has been correctly noted by Ma et al. [40] that the optimal fertilization of oilseed rape is necessary to obtain high yields but, at the same time, the best economic effect of the applied fertilizers.

5. Conclusions

Foliar fertilization allows for obtaining larger and qualitatively better seed yields. The conducted experiment demonstrated that the best results were achieved during intensive application of foliar fertilizers. The preparations used in variants D and E resulted in a significant increase in the number of pods per plant, SPAD index and LAI compared to the control. Leaf stomatal conductance (Gs) was the highest after foliar fertilization in variant D. High seed yields were obtained after intensive foliar fertilization (variants E and D). Higher fat concentration was determined after applying fertilization variant D compared to the control. The fat yield per hectare was the highest after the application of intensive foliar fertilization (variants D and E). The protein content in control seeds was over 20%, while foliar fertilization in variant D reduced this component concentration in seeds. The protein yield was the highest after the application of fertilizers in variants C and E. It was shown that intensive foliar fertilization (variants D and E) significantly increased seed boron content compared to YaraVita Thiotrac fertilization and the control. The best economic effect was obtained after the application of intensive foliar fertilization in variants D and E. Therefore, the results of the application of foliar fertilizers in winter oilseed rape were dependent on the selection of the appropriate fertilization variant.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agriculture11060515/s1>, Table S1: Yield components and seed yield, mean values for interaction foliar fertilization x years. Table S2: Chemical composition of seeds and yield of fat and protein, mean values for interaction foliar fertilization x years. Table S3: Field measurements of SPAD, LAI and Gs indices, mean values for interaction foliar fertilization x years.

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