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Winter Oilseed Rape: Agronomic Management in Different Tillage Systems and Seed Quality

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Abstract: A three-year study was conducted to analyze agronomic management in the production of winter oilseed rape (WOSR) under different tillage systems. A field experiment was conducted at the University's Agricultural Experiment Station in Bałcyny (north-eastern Poland), in three growing seasons (2016/2017, 2017/2018, and 2018/2019). The experiment had a 3^{5-2} resolution III fractional factorial design with five fixed factors that were tested at three levels of intensity. The experimental factors were: A—tillage: (A0) strip-till, (A1) low-till, (A2) conventional tillage; B—weed control: (B0) pre-emergent, (B1) foliar, (B2) sequential; C—growth regulation: (C0) none, (C1) in fall, (C2)—in fall and spring; D—rate of nitrogen (N) fertilizer applied in spring: (D0) 160, (D1) 200, (D2) 240 kg ha^{-1}; and E—rate of sulfur (S) fertilizer applied in spring: (E0) 0, (E1) 40, (E2) 80 kg ha^{-1}. The crude fat (CF) content of WOSR seeds was highest in the strip-till system (498 g kg^{-1} dry matter, DM), and the total protein (TP) content of seeds was highest (196 g kg^{-1} DM) in low-till and conventional tillage systems. The content of neutral detergent fiber (NDF) was higher in seeds harvested from strip-till and low-till systems than from the conventional tillage system. The seeds of WOSR plants grown in the conventional tillage system accumulated more (by 0.4%) polyunsaturated fatty acids (PUFAs) and less (by 0.5–0.6%) monounsaturated fatty acids (MUFAs). An increase in the N rate from 160–200 to 240 kg ha^{-1} decreased the CF content (495 vs. 484 g kg^{-1} DM) and increased the TP content of seeds (191 vs. 199 g kg^{-1} DM). Sulfur fertilization induced a 34% increase in glucosinolate (GLS) concentrations in WOSR seeds, mainly by enhancing the biosynthesis of alkenyl GLS (by 39%).

Keywords: *Brassica napus* (L.); tillage; weed control; growth regulators; nitrogen and sulfur fertilization; seed quality

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1. Introduction

Food crops that store carbohydrates as energy reserves (cereals, potatoes, sweet potatoes, etc.) are considered the most economically important around the world. In developing countries, cereals account for as much as 60% of the caloric intake. In developed countries, cereal consumption is relatively high (35% of the caloric intake), but the consumption of fat, including vegetable fats, has also increased [1]. The role of vegetable oils has increased with rapid economic and population growth in the industrial age, and breeding progress (modification of the fatty acid composition of rapeseed—the most important oilseed crop in the temperate zone) [2,3]. In 2010–2020, the global production of four major vegetable oils increased by 5.7 mln Mg per year on average, to reach around 201 mln Mg in the 2020/2021 season, where palm oil (from the fruit of oil palm trees) accounted for 38%, followed by soybean oil—30%, canola oil—14%, and sunflower oil—9% [4].

In terms of nutritional value, oil extracted from the seeds of double-low (canola-quality) rapeseed cultivars is characterized by the most favorable fatty acid profile due to a high content of oleic acid (which decreases blood cholesterol levels), a desirable n-6/n-3

PUFA ratio, a very low content (approx. 6–7%) of nutritionally undesirable saturated fatty acids (SFAs), and an optimal proportion of linolenic acid (which improves neurological function) [5]. Rapeseed oil is used for both culinary and industrial purposes: it is suitable for short-term deep frying, margarine production, production of liquid biofuel components (biodiesel), dyes, varnishes, solvents, etc. [2].

Fat-free residues of rapeseeds are the second most commonly used protein source for livestock after soybean meal [6]. Rapeseed meal is characterized by a favorable amino acid profile, including a relatively high content of exogenous amino acids (methionine and cystine) and minerals (phosphorus and calcium) [7,8]. Even though the concentrations of anti-nutritional factors in seeds of canola cultivars have been considerably reduced, the presence of GLS still decreases the feed value of fat-free seed residues. These compounds impart a bitter flavor to rapeseed press-cake and meal, decrease protein availability, and inhibit the synthesis of thyroid hormones; they may also cause liver damage. Alkenyl GLS exert the most detrimental effects [9]. Fiber is the main factor responsible for decreasing the digestibility and energy value of rapeseed press-cake and meal, and fiber content is nearly twice as high in rapeseed meal than in soybean meal [10].

The quality of rapeseeds is determined by genetic factors (cultivar) and environmental conditions, but it can be considerably modified by agronomic factors and production technology [11]. Tillage and seeding methods have a minor influence on the content of crude fat (CF) and total protein (TP) in the seeds of winter oilseed rape (WOSR) [12–16]. Muśnicki et al. [12,13] demonstrated that shallow pre-sowing plowing increased CF concentration in WOSR seeds by approximately 1%. In turn, Jankowski [16] found that WOSR seeds had lower CF content in the conventional tillage system, compared with simplified tillage. Different tillage systems have no significant effect on TP concentration in WOSR seeds [12–16].

Weeds can considerably compromise the quality and market value of WOSR seeds [17]. Some weed species (e.g., *Sinapis arvensis* L. and *Thlaspi arvense* L.) decrease seed quality by increasing the content of erucic acid and GLS. In canola cultivars, effective weed management contributes to an increase (by up to 10%) in the CF content of seeds [17]. In turn, the absence of chemical weed control significantly affects the fatty acid profile of seeds [17,18].

Growth regulators applied in autumn exert a minor influence on nutrient synthesis in WOSR seeds [16,19]. In a study by Ijaz and Honermeier [19], the CF content of WOSR seeds peaked (454–455 g kg^{-1} dry matter, DM) in the control treatment and after the autumn application of tebuconazole and trinexapac-ethyl. The accumulation of CF in seeds decreased significantly (to 450 g kg^{-1} DM) following the application of metconazole. In contrast, Jankowski [16] observed no significant differences in the concentrations of CF or TP in WOSR seeds in response to growth regulation in autumn.

Chemical growth regulation in spring exerted varied effects on nutrient synthesis in WOSR seeds [20–22]. Ijaz and Honermeier [19], and Matysiak and Kaczmarek [21] found no relationships between the spring application of metconazole, tebuconazole, trinexapac-ethyl [19], and chlorocholine chloride [21] vs. the content of CF and TP in WOSR seeds. Ijaz and Honermeier [19] demonstrated that metconazole induced a minor increase (2%) in the CF content of WOSR seeds, whereas Ijaz et al. [22] observed a slight decrease (2%) in the CF content of WOSR seeds when mixtures of tebuconazole and prothioconazole, and difenoconazole and paclobutrazole, were applied in spring. The application of azoxystrobin in combination with triazole fungicides stimulated the synthesis of CF in WOSR seeds, most likely due to prolonged seed formation [22]. Matysiak et al. [23] reported that the timing of growth regulator application (BBCH 30 vs. 50) may affect the quality of WOSR seeds. The CF content of seeds peaked after the application of metconazole (regardless of application timing) and tebuconazole (at BBCH 30). Growth regulators also exert varied effects on the fatty acid profile. The spring application of trinexapac-ethyl increased the concentration of linolenic acid in rapeseed oil by 3% [20], whereas the autumn and spring application of metconazole decreased the concentration of oleic acid by 1% [19].

Nitrogen fertilization is a key determinant of seed quality in WOSR cultivation [16,24,25]. Many researchers have found that increasing N rates induce a decrease in CF concentration [16,24–32] and enhance TP synthesis in WOSR seeds [16,24,27–30]. Nitrogen application in later growth stages has a particularly adverse effect on CF accumulation in WOSR seeds. Nitrogen applied at the beginning of flowering contributes to an increase in the TP content and a decrease in the CF content of WOSR seeds [1,24].

Sulfur fertilization may have different effects on the nutrient content of WOSR seeds. According to Sienkiewicz-Cholewa and Kieloch [33] and Fazili et al. [34], S promotes CF accumulation in seeds. In turn, Wielebski [35] demonstrated that CF synthesis decreased, and TP concentration increased in WOSR seeds in response to S fertilizer. Jankowski et al. [36,37] and Groth et al. [38] found that S fertilization had no significant influence on the content of CF or TP in WOSR seeds. Sulfur considerably modifies GLS concentrations in the biomass of *Brassicaceae* oilseed crops [37]. In experiments conducted by Jankowski [16] and Groth et al. [38], S application increased GLS accumulation in WOSR seeds by up to 24–29%. It should be noted that S fertilization increases the content of alkenyl GLS, by 13–15% [35,39] and up to 40% [38]. The synthesis of indole GLS is less stimulated by S application, and the S-induced increase in their concentration has been estimated at 5–15% [35–37,39].

The aim of this study was to determine the effects of weed control, growth regulation, and N and S fertilization on the quality of seeds harvested from WOSR plants grown in different tillage systems (conventional tillage, low-till, and strip-till). Five agronomic factors were evaluated at three levels of intensity in a small-area field experiment with a 3^{5-2} fractional factorial design. The main effects and two-factor interaction effects were evaluated with the use of modified fractional design generators [1,40,41].

2. Materials and Methods

2.1. Field Experiment

The presented results were obtained during a small-area field experiment carried out in 2016–2019 at the Agricultural Experiment Station (AES) in Bałcyny (NE Poland, 53°35′46.4′′ N, 19°51′19.5′′ E). The experiment had a 3^{5-2} resolution III fractional factorial design with two replications, where five agronomic factors (A, B, C, D, and E) were tested at three intensity levels (0, 1, and 2) (Table 1).

Table 1. Experimental factors.

Symbol	Agricultural Operation	Level		
		0	1	2
A	Tillage †	strip-till	low-till	conventional tillage
B	Weed control	pre-emergent (0–2 days after sowing) 500 g ha^{-1} metazachlor, 500 g ha^{-1} dimethenamid-P, 250 g ha^{-1} quinmerac	Foliar (BBCH 12–14 ††) 72 g ha^{-1} clopyralid, 24 g ha^{-1} picloram, 12 g ha^{-1} aminopyralid, 750 g ha^{-1} metazachlor	(0–2 days after sowing) 72 g ha^{-1} clomazone (BBCH 12–14) 72 g ha^{-1} clopyralid, 24 g ha^{-1} picloram, 12 g ha^{-1} aminopyralid
C	Growth regulation	none	fall treatment (BBCH 14–15) 210 g ha^{-1} mepiquat chloride, 30 g ha^{-1} metconazole	(BBCH 14–15) 210 g ha^{-1} mepiquat chloride, 30 g ha^{-1} metconazole (BBCH 30–31) 125 g ha^{-1} difenoconazole, 62.5 g ha^{-1} paclobutrazol
D	Spring N rate (kg ha^{-1}) †††	160 (120 + 40) (BBCH 20–30 + 50)	200 (120 + 80) (BBCH 20–30 + 50)	240 (120 + 120) (BBCH 20–30 + 50)
E	Spring S rate (kg ha^{-1}) ††††	0	40 (BBCH 20–30)	80 (BBCH 20–30)

† strip-till with sowing and application of NPK fertilizers to a depth of 10 and 20 cm (50:50%); low-till to a depth of 25–30 cm one day before sowing with a seed drill cultivator; conventional tillage—disking to a depth of 5–8 cm after harvesting the previous crop, pre-sowing plowing to a depth of 18–20 cm 7–10 days before sowing, seedbed preparation, and sowing with a seed drill cultivator. †† Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [42]: BBCH 12–14—2–4 true leaves unfolded; BBCH 14–15—4–5 true leaves unfolded; BBCH 20–30—beginning of the spring growing season; BBCH 30–31—rosette regrowth after winter; BBCH 50—beginning of the budding stage. ††† N fertilizer was applied before the spring growing season (BBCH 20–30) at 120 kg N ha^{-1} in the form of: (i) ammonium nitrate (treatments D0E0, D1E0, D2E0) or (ii) ammonium sulfate and ammonium nitrate (treatments D0E1, D1E1, D2E1, D0E2, D1E2, D2E2). The second N rate was applied as ammonium sulfate in BBCH stage 50. †††† Sulfur was applied as ammonium sulfate.

The harvested plot areas were 15 m^2 each (10 m by 1.5 m). Winter wheat was the preceding crop in each year of the study. To prepare the plots for WOSR cultivation, winter wheat was cut to a height of 12–15 cm, and the entire straw was collected. The experiment was established on Haplic Luvisol originating from boulder clay [43] with a slightly acidic pH (pH KCl 5.6–6.2) and C_{org} content of 1.04–1.28%. The macronutrient and micronutrient content of the arable layer was determined at: 91.0–221.0 P_2O_5 mg kg^{-1}, 145.0–195.0 K_2O mg kg^{-1}, 89.0–129.3 Mg mg kg^{-1}, 4.4–13.3 SO_4^{2-} mg kg^{-1}, 0.14–0.44 B mg kg^{-1}, 128.0–218.0 Mn mg kg^{-1}, 2.1–4.5 Cu mg kg^{-1}, 5.6–11.8 Zn mg kg^{-1}, and 1680–2000 Fe mg kg^{-1}. The content of C_{org} in soil was determined by the modified Kurmies method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan). Soil pH was measured with a digital pH meter with temperature compensation (20 °C) in deionized water and 1 mol KCl (5:1). Plant-available P and K were extracted with calcium lactate (Egner–Riehm method). Phosphorus was measured by vanadium-molybdenum yellow spectrophotometry (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan), and K was measured by atomic emission spectrometry (AES) (Flame Photometers, BWB Technologies Ltd., Newbury, UK). Magnesium was extracted with 0.01 mol of calcium chloride and quantified by atomic absorption spectrophotometry (AAS) (AAS1N, Carl Zeiss, Jena, Germany). Boron concentration was determined colorimetrically (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan), and the concentrations of Cu, Zn, Mn, and Fe were determined by AAS after extraction in 1 mol dm^{-3} HCl. The content of sulfide sulfur was analyzed by nephelometry after extraction in an acetate buffer (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan).

The seeds of the hybrid WOSR cultivar Kuga were sown between 13 and 23 August at 50 germinating seeds per 1 m^2. Agronomic factors that did not constitute the experimental variables were applied according to good agricultural practice. The following fertilizers were applied before sowing: 40 kg N ha^{-1} (urea), 60 kg P_2O_5 ha^{-1} (enriched superphosphate), and 120 kg K_2O ha^{-1} (potash salt). In the strip-till system (A0), fertilizers were applied together with seeds to a depth of 10 and 20 cm at 50:50%. In low-till (A1) and conventional tillage (A2) systems, fertilizers were distributed on the surface of previous crop residues (stubble). In all treatments, monocotyledonous weeds were controlled with 60 g ha^{-1} propaquizafop (BBCH 12–14). Foliar B fertilizer (2 × 175 g B ha^{-1}) was applied twice in spring (BBCH 20–30 and 50). Pests were controlled chemically in BBCH stages 35–37 (300 g ha^{-1} chlorpiryfos + 30 g ha^{-1} cipermetrin) and BBCH stages 63–67 (60 g ha^{-1} thiacloprid + 6 g ha^{-1} deltamethrin) when the action threshold was exceeded. Fungal diseases were managed with 100 g ha^{-1} dimoxystrobin and 100 g ha^{-1} boscalid (BBCH 63). Winter oilseed rape was harvested at physiological maturity (8–24 July) with a small-plot harvester.

2.2. Seed Quality

The quality of WOSR seeds was evaluated based on the following parameters: the content of CF and TP (in g kg^{-1} DM seeds), proportions of neutral detergent fiber (NDF) and acid detergent fiber (ADF) (in %), fatty acid profile (in %), and the content of total GLS and alkenyl GLS (in μM g^{-1} DM seeds).

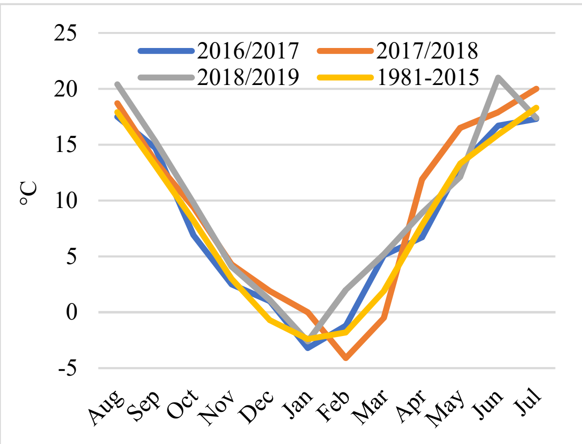
Winter oilseed rape seeds were scanned with the use of a NIR Systems 650 near-infrared reflectance spectrometer (FOSS NIR Systems Inc., Silver Spring, USA). A calibration equation derived in the WINISI program was used in the measurements based on the reference data for Kjeldahl (TP), Soxhlet (CF), and van Soest (NDF and ADF) methods. Glucosinolate content was quantified by gas chromatography of trimethylsilyl derivatives of desulfated GLS in the Agilent 7890 gas chromatograph with an HP-5 column (Agilent Technologies Inc., Santa Clara, USA), using the method described by Raney and modified by Michalski et al. [44]. Fatty acid composition was determined by methylation of oil extracted from 0.1 g of ground seeds. Fatty acid methyl esters (FAMEs) were analyzed by gas chromatography (HP 3390A integrator, Hewlett-Packard, Avondale, USA) with a DB-23 capillary column (length: 30 m); operating temperature—200°C (injector and detector temperature—220°C); carrier gas—hydrogen.

2.3. Statistical Analysis

The original 3^{5-2} fractional factorial design with resolution III and 27 treatments per replication was initially generated. However, the experiment involved three growing seasons, which generated large quantities of data for analysis; therefore, in the statistical analysis, the original 3^{5-2} ANOVA model was reduced to 21 treatments, but all attributes of the 3^{5-2} design (III) were retained. Based on this analytical model, ANOVA was used to evaluate the main effects of all fixed factors (A, B, C, D, and E) and their interactions with the random effects of the experimental years (Y × A, Y × B, Y × C, Y × D, and Y × E). The significance of differences between mean values was determined in Tukey's honest significant difference (HSD) test with $p < 0.05$. All analyses were performed in the Statistica 13.3 program [45]. The *F*-values in ANOVA are presented in Table 2.

2.4. Weather Conditions

The weather conditions during the three growing seasons are presented in Figure 1. In all years of the study, the mean daily temperature during the autumn growing season (August-November) was similar to the long-term average (10.3–11.3 vs. 11.4 °C). Different temperatures were noted during winter dormancy (December-March) and the spring-summer growing season (April–July). In the 2018/2019 season, the mean daily temperature during winter dormancy was 1.3 °C higher than the long-term average (0.0 °C). In the remaining years, the mean daily temperature during winter dormancy was comparable to the long-term average. During the spring-summer growing season, the highest mean daily temperature was recorded in 2017/2018, and it exceeded the long-term average by 2.3 °C (15.6 vs. 13.3 °C). In the remaining years, the mean daily temperature during the spring-summer growing season approximated the long-term average (12.9–13.8 vs. 13.3 °C). In the study area, the mean rainfall during the growing season over the last 35 years was 514 mm. In the first and second years of the study, total rainfall during the growing season exceeded the long-term average by 27 and 38%, respectively (655–707 vs. 514 mm). In the third year, precipitation was 9% lower than the long-term average (Figure 1).



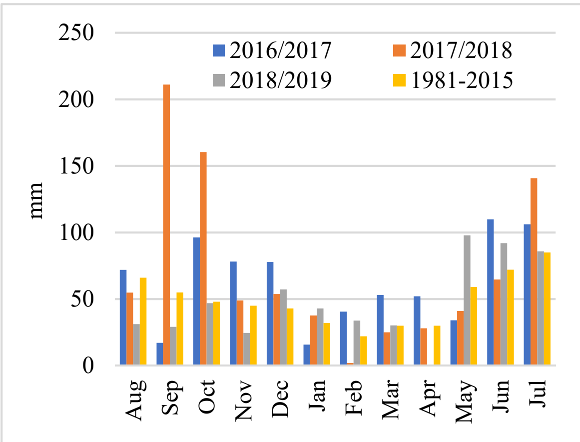


Figure 1. Mean monthly temperature (°C) and total monthly precipitation (mm) during the growing seasons of 2016–2019 vs. the long-term average (1981–2015).

Table 2. *F*-test statistics in ANOVA of seed quality in WOSR production.

Source of Variation	Effect	Crude Fat (g kg^{-1} DM)	Total Protein (g kg^{-1} DM)	NDF (%)	ADF (%)	GLS (μM g^{-1})		Fatty Acids (%)								
						Alkenyl	Total	C16:0	C18:0	C18:1	C18:2	C18:3	C20:1	SFAs	MUFAs	PUFAs
Growing season (Y)	random	114.76 **	67.16 **	79.49 **	20.88 **	8.28 **	40.84 **	59.50 **	182.33 **	146.15 **	99.25 **	303.69 **	24.20 **	34.16 **	197.69 **	213.71 **
Tillage system (A)	fixed	7.64 **	4.61 **	5.21 **	1.20 *ns*	0.86 *ns*	2.24 *ns*	2.00 *ns*	1.57 *ns*	5.75 **	1.49 *ns*	9.06 **	0.46 *ns*	2.84 *ns*	7.09 **	5.13 *
Weed control (B)	fixed	0.36 *ns*	0.21 *ns*	0.20 *ns*	0.66 *ns*	0.05 *ns*	0.36 *ns*	1.07 *ns*	0.16 *ns*	0.48 *ns*	0.10 *ns*	0.87 *ns*	2.55 *ns*	1.31 *ns*	0.34 *ns*	0.43 *ns*
Growth regulation €	fixed	0.11 *ns*	0.09 *ns*	0.22 *ns*	0.04 *ns*	0.04 *ns*	0.00 *ns*	2.66 *ns*	0.42 *ns*	0.64 *ns*	4.13 *ns*	0.31 *ns*	18.80 **	2.60 *ns*	2.39 *ns*	2.80 *ns*
Nitrogen fertilization (D)	fixed	10.10 **	6.32 **	11.06 **	0.79 *ns*	0.18 *ns*	0.14 *ns*	0.08 *ns*	0.48 *ns*	0.43 *ns*	0.85 *ns*	0.86 *ns*	0.51 *ns*	0.08 *ns*	0.24 *ns*	0.50 *ns*
Sulfur fertilizati€(E)	fixed	3.47 *ns*	0.53 *ns*	3.62 *ns*	0.05 *ns*	5.15 **	6.02 **	2.04 *ns*	0.09 *ns*	0.70 *ns*	0.02 *ns*	0.92 *ns*	1.60 *ns*	2.16 *ns*	0.11 *ns*	0.13 *ns*
Y × A	random	0.14 *ns*	1.38 *ns*	2.07 *ns*	0.79 *ns*	0.61 *ns*	0.96 *ns*	1.27 *ns*	1.33 *ns*	0.42 *ns*	0.53 *ns*	1.36 *ns*	1.63 *ns*	1.24 *ns*	0.66 *ns*	0.80 *ns*
Y × B	random	0.26 *ns*	0.77 *ns*	0.93 *ns*	1.26 *ns*	0.37 *ns*	0.53 *ns*	1.09 *ns*	1.32 *ns*	0.12 *ns*	0.70 *ns*	0.30 *ns*	0.23 *ns*	1.15 *ns*	0.20 *ns*	0.52 *ns*
Y × C	random	3.29 **	0.91 *ns*	1.73 *ns*	0.45 *ns*	1.12 *ns*	1.26 *ns*	2.68 *ns*	1.28 *ns*	0.25 *ns*	0.34 *ns*	0.09 *ns*	1.62 *ns*	3.09 *ns*	1.30 *ns*	0.21 *ns*
Y × D	random	0.98 *ns*	1.62 *ns*	1.64 *ns*	0.97 *ns*	0.17 *ns*	0.51 *ns*	0.83 *ns*	0.91 *ns*	0.28 *ns*	0.78 *ns*	0.60 *ns*	0.49 *ns*	0.61 *ns*	0.44 *ns*	0.61 *ns*
Y × E	random	2.46 *ns*	0.40 *ns*	2.44 *ns*	0.29 *ns*	2.02 *ns*	2.39 *ns*	2.37 *ns*	2.01 *ns*	2.05 *ns*	5.42 **	1.24 *ns*	13.32 **	2.74 *ns*	6.32 **	4.55 *

ADF—acid detergent fiber; NDF—neutral detergent fiber; GLS—glucosinolates; C16:0—palmitic acid; C18:0—stearic acid; C18:1—oleic acid; C18:2—linoleic acid; C18:3—linolenic acid; C20:1—eicosenoic acid; SFAs—saturated fatty acids; MUFAs—monounsaturated fatty acids; PUFAs—polyunsaturated fatty acids. * significant $p < 0.05$; ** significant $p < 0.01$; *ns*—not significant.

3. Results

3.1. Years

In the first and second years of the study, which were characterized by above-average precipitation in spring and summer, WOSR seeds accumulated the highest quantities of CF. The proportions of both crude fiber fractions (NDF and ADF) in WOSR seeds also increased in years with abundant rainfall between April and July. Lower precipitation levels during the spring-summer growing season (2018/2019) contributed to the accumulation of TP and GLS in WOSR seeds (Table 3). Above-average rainfall in spring and summer (years 1 and 2) supported the synthesis of SFAs (mostly palmitic acid) and PUFAs (mostly linoleic acid and linolenic acid). In the third year of the study, the proportions of SFAs and PUFAs were 0.73% and 3.69% lower, respectively. Lower precipitation levels during the spring-summer growing season (year 3) promoted the synthesis of oleic acid and eicosenoic acid (MUFAs) (Table 4).

Table 3. Nutritional value of WOSR seeds (main factors).

Agronomic Factor	Level	Crude Fat (g kg^{-1} DM)	Total Protein (g kg^{-1} DM)	NDF (%)	ADF (%)	Σ alkenyl GLS (μM g^{-1} DM)	Σ GLS (μM g^{-1} DM)
Years	2016/2017	519.1 ^{a}	175.3 ^{c}	28.5 ^{a}	23.6 ^{a}	6.07 ^{b}	8.84 ^{b}
	2017/2018	496.4 ^{b}	189.1 ^{b}	27.6 ^{b}	21.7 ^{b}	5.16 ^{b}	6.47 ^{c}
	2018/2019	457.1 ^{c}	216.3 ^{a}	26.1 ^{c}	20.5 ^{c}	7.47 ^{a}	11.64 ^{a}
Tillage	strip-till	497.6 ^{a}	188.6 ^{b}	27.6 ^{a}	22.2	5.85	8.38
	low-till	489.4 ^{ab}	196.4 ^{a}	27.4 ^{ab}	21.5	6.41	9.12
	conventional tillage	485.6 ^{b}	195.8 ^{a}	27.1 ^{b}	22.0	6.45	9.45
Weed control	pre-emergent	489.8	191.9	27.5	22.0	5.93	8.42
	foliar	492.3	193.7	27.4	22.1	6.28	9.20
	sequential	490.2	195.5	27.4	21.6	6.54	9.35
Growth regulation	none	484.6	195.1	27.1	21.6	5.16	7.54
	BBCH 14–15	492.1	194.4	27.5	21.9	6.98	9.94
	BBCH 14–15 and 30–31	493.6	191.9	27.4	22.1	6.16	8.93
Spring nitrogen rate (kg N ha^{-1})	160	494.5 ^{a}	190.5 ^{b}	27.6 ^{a}	22.0	6.18	8.81
	200	494.1 ^{a}	192.5 ^{ab}	27.5 ^{a}	22.1	6.24	9.11
	240	483.8 ^{b}	198.7 ^{a}	27.0 ^{b}	21.7	6.31	9.16
Spring sulfur rate (kg S ha^{-1})	0	483.7	195.2	27.1	21.7	5.18 ^{c}	7.60 ^{c}
	40	493.6	191.9	27.4	22.1	6.16 ^{b}	8.93 ^{b}
	80	493.9	194.2	27.6	21.9	7.23 ^{a}	10.23 ^{a}

ADF—acid detergent fiber; NDF—neutral detergent fiber; GLS—glucosinolates. BBCH 14–15—4–5 true leaves unfolded; BBCH 30–31—rosette regrowth after winter. Means sharing a common letter are not significantly different at $p \leq 0.05$ in Tukey's test. The absence of common letters denotes non-significant differences (*ns*) at $p \leq 0.05$ in Tukey's test.

Table 4. Fatty acids (%) (main factors).

Agronomic Factor	Level	C16:0	C18:0	C18:1	C18:2	C18:3	C20:1	SFAs	MUFAs	PUFAs
Years	2016/2017	4.27 ^{a}	1.32 ^{c}	62.40 ^{c}	20.92 ^{a}	10.10 ^{a}	1.00 ^{b}	5.59 ^{a}	63.39 ^{c}	31.02 ^{a}
	2017/2018	4.20 ^{a}	1.52 ^{b}	65.23 ^{b}	19.23 ^{b}	8.80 ^{b}	1.01 ^{b}	5.72 ^{a}	66.24 ^{b}	28.04 ^{b}
	2018/2019	3.12 ^{b}	1.74 ^{a}	66.31 ^{a}	19.48 ^{b}	7.86 ^{c}	1.49 ^{a}	4.86 ^{b}	67.80 ^{a}	27.33 ^{c}
Tillage	strip-till	3.81	1.53	64.85 ^{a}	19.85	8.81 ^{b}	1.15	5.34	66.00 ^{a}	28.66 ^{b}
	low-till	3.85	1.51	64.84 ^{a}	19.81	8.84 ^{b}	1.15	5.36	65.99 ^{a}	28.66 ^{b}
	conventional tillage	3.93	1.54	64.25 ^{b}	19.97	9.10 ^{a}	1.20	5.48	65.45 ^{b}	29.07 ^{a}
Weed control	pre-emergent	3.88	1.53	64.58	19.89	8.93	1.19	5.41	65.77	28.82
	foliar	3.82	1.53	64.61	19.89	8.95	1.20	5.34	65.81	28.85
	sequential	3.91	1.53	64.77	19.85	8.86	1.09	5.43	65.86	28.71

Table 4. *Cont.*

Agronomic Factor	Level	C16:0	C18:0	C18:1	C18:2	C18:3	C20:1	SFAs	MUFAs	PUFAs
Growth regulation	none	3.88	1.52	64.31	20.17	9.01	1.11	5.40	65.42	29.18
	BBCH 14–15	3.84	1.54	64.92	19.69	8.83	1.19	5.38	66.11	28.52
	BBCH 14–15 and 30–31	3.88	1.52	64.59	19.89	8.95	1.18	5.40	65.76	28.84
Spring nitrogen rate (kg N ha^{-1})	160	3.86	1.54	64.60	19.93	8.91	1.17	5.40	65.77	28.84
	200	3.88	1.52	64.83	19.71	8.92	1.16	5.39	65.98	28.63
	240	3.86	1.52	64.61	19.90	8.94	1.17	5.38	65.78	28.84
Spring sulfur rate (kg S ha^{-1})	0	3.86	1.53	64.28	20.11	9.03	1.19	5.38	65.48	29.14
	40	3.88	1.52	64.59	19.89	8.95	1.18	5.40	65.76	28.84
	80	3.85	1.53	65.02	19.67	8.79	1.13	5.39	66.16	28.46

C16:0—palmitic acid; C18:0—stearic acid; C18:1—oleic acid; C18:2—linoleic acid; C18:3—linolenic acid; C20:1—eicosenoic acid; SFAs—saturated fatty acids; MUFAs—monounsaturated fatty acids; PUFAs—polyunsaturated fatty acids. BBCH 14–15—4–5 true leaves unfolded; BBCH 30–31—rosette regrowth after winter. Means sharing a common letter are not significantly different at $p \leq 0.05$ in Tukey's test. The absence of common letters denotes non-significant differences (*ns*) at $p \leq 0.05$ in Tukey's test.

3.2. Tillage

Winter oilseed rape grown in low-till and conventional tillage systems accumulated 2–3% less CF and 4% more TP in the seeds than WOSR grown in the strip-till system (Table 3). The content of NDF was higher in seeds harvested from strip-till (27.6%) and low-till (27.4%) systems than those harvested from the conventional tillage system (27.1%). The tillage system did not significantly affect ADF and GLS levels in the seeds (Table 3). The seeds of WOSR plants grown in the conventional tillage system accumulated 0.4% more PUFAs (mostly due to enhanced synthesis of linolenic acid) and 0.5–0.6% less MUFAs (mostly due to a lower proportion of oleic acid) (Table 4). The effects of different tillage systems on the analyzed seed quality parameters were not modified by weather conditions (Y × A) (Table 2).

3.3. Weed Control

None of the tested weed control methods induced significant differences in seed quality parameters, regardless of weather conditions across the years (Y × B) (Table 2).

3.4. Growth Regulation

In years 1 and 2, growth regulators increased the CF content of seeds by 11–61 (fall treatment) to 7–25 g kg^{-1} DM (fall and spring treatments). A reverse relationship was observed in year 3, when growth regulators decreased the CF content of seeds by around 5 g kg^{-1} DM (Table 5). No relationships were found between the application of growth regulators vs. fatty acid profile, and the content of protein, ADF, NDF, and GLS in seeds, regardless of weather conditions (Y × C) (Table 2).

Table 5. The effect of growth regulation on the CF content (g kg^{-1} DM) of WOSR seeds (Y × C).

Growing Season	Growth Regulation at		
	None	BBCH 14–15	BBCH 14–15 and 30–31
2016/2017	512.5 ^{ab}	523.2 ^{a}	519.1 ^{a}
2017/2018	480.5 ^{b}	496.9 ^{b}	505.9 ^{ab}
2018/2019	460.9 ^{bc}	456.0 ^{c}	455.8 ^{c}

BBCH 14–15—4–5 true leaves unfolded; BBCH 30–31—rosette regrowth after winter. Means sharing a common letter are not significantly different at $p \leq 0.05$ in Tukey's test. The absence of common letters denotes non-significant differences (*ns*) at $p \leq 0.05$ in Tukey's test.

3.5. Spring Nitrogen Fertilization

An increase in the N rate from 160 to 200 kg ha^{-1} did not induce significant changes in the content of CF and TP in WOSR seeds (Table 3). In turn, the application of 240 kg N ha^{-1} decreased the CF content (by 10.5 g kg^{-1} DM on average) and increased the TP content (by 7.2 g kg^{-1} DM on average) of WOSR seeds. In addition, the highest N rate (240 kg ha^{-1}) induced a significant decrease in the proportion of NDF (by 0.4–0.5%). The quality of oil (fatty acids) and fat-free seed residues (determined based on the concentrations of total GLS and alkenyl GLS) was not significantly differentiated by spring-applied N rates (Table 2). The effect of N fertilization on the analyzed seed quality parameters was not influenced by weather conditions across the years of the study (Y × D) (Table 2).

3.6. Spring Sulfur Fertilization

Sulfur fertilization (0, 40, and 80 kg ha^{-1}) had no influence on the content of CF, TP, ADF, or NDF in WOSR seeds. A relationship was found between S fertilization and the fatty acid profile of WOSR oil depending on weather conditions (Table 2). An increase in S rate to 80 kg ha^{-1} induced a significant decrease (by 0.49–0.69%) in the concentration of linoleic acid in years when spring and summer precipitation approximated the long-term average (2016/2017 and 2017/2018) (Table 6). The concentration of eicosenoic acid increased (by 0.20%) in response to S fertilizer applied in the year characterized by below-average precipitation in April–July (2018/2019). A rise in the S rate in 2018/2019 (below-average precipitation) contributed to a significant increase in the proportion of PUFAs (by 0.48%) and a decrease in the proportion of MUFAs (0.58%) in WOSR oil (Table 6). Sulfur exerted a strong influence on the content and structure of GLS in seeds (Table 2). The application of 40 and 80 kg S ha^{-1} increased the content of total GLS (by 18% and 35%, respectively) and alkenyl GLS (by 19% and 40%, respectively) in WOSR seeds (Table 3). The proportion of alkenyl GLS in total GLS increased from 68% to 71% under the influence of S fertilization.

Table 6. The effect of spring sulfur rate on the proportions of fatty acids (%) in WOSR oil (Y × E).

Growing Season	Spring Sulfur Rate (kg ha^{-1})		
	0	**40**	**80**
	C18:2		
2016/2017	21.23 ^{a}	21.03 ^{a}	20.54 ^{ab}
2017/2018	19.90 ^{b}	19.03 ^{cd}	18.90 ^{d}
2018/2019	19.18 ^{bc}	19.61 ^{bc}	19.57 ^{bc}
	C20:1		
2016/2017	1.00 ^{c}	1.01 ^{c}	0.97 ^{c}
2017/2018	1.02 ^{c}	0.98 ^{c}	1.06 ^{c}
2018/2019	1.57 ^{a}	1.57 ^{a}	1.37 ^{b}
	MUFAs		
2016/2017	62.93 ^{d}	63.19 ^{d}	64.01 ^{d}
2017/2018	65.28 ^{c}	66.46 ^{b}	66.81 ^{ab}
2018/2019	68.22 ^{a}	67.64 ^{ab}	67.64 ^{ab}
	PUFAs		
2016/2017	31.48 ^{a}	31.19 ^{ab}	30.43 ^{b}
2017/2018	28.95 ^{c}	27.84 ^{d}	27.49 ^{d}
2018/2019	26.98 ^{d}	27.49 ^{d}	27.46 ^{d}

C18:2—linoleic acid; C20:1—eicosenoic acid; MUFAs—monounsaturated fatty acids; PUFAs—polyunsaturated fatty acids. Means sharing a common letter are not significantly different at $p \leq 0.05$ in Tukey's test.

4. Discussion

4.1. Tillage

In a study by Jankowski and Budzyński [15], a reduction in the depth of pre-sowing tillage from 30 cm to 10 cm decreased the CF and TP content of seeds by 15 and 3 g kg^{-1}

DM, respectively. In turn, Muśnicki et al. [12,14] demonstrated that a decrease in plowing depth (from 30–32 cm to 10–12 cm) increased the accumulation of CF and TP in seeds by 10 and 18 g kg^{-1} DM, respectively. According to Jankowski [16], a reduction in tillage depth (from 22 cm to 12 cm) increased the CF content of seeds by 8 g kg^{-1} DM. In comparison with conventional tillage, low-till farming and direct sowing decreased the CF content of seeds by around 6–8 g kg^{-1} DM. In the work of Jankowski [16], the TP content of WOSR seeds was not differentiated by the applied tillage implements or plowing depth. In the present study, simplified tillage promoted the accumulation of CF in WOSR seeds. Crude fat content was highest in seeds produced in the strip-till system (497.6 g kg^{-1} DM), followed by seeds grown in the conventional tillage system (lower by 12 g kg^{-1} DM). The TP content of WOSR seeds was lowest in the strip-till system (189 kg^{-1} DM).

4.2. Weed Control

Weed infestation in WOSR stands not only decreases seed yields but also compromises their quality and commercial value [1]. The timing of herbicide application exerts an ambiguous effect on the quality of WOSR seeds. In a study by Adomas [18], the CF content of spring oilseed rape was higher in treatments protected with pre-emergent herbicides (456 g kg^{-1} DM) than those protected with foliar herbicides (451 g kg^{-1} DM). In turn, Hamzei et al. [46] found no correlation between the weed control method and the CF content of WOSR seeds. In the experiment carried out by Gołębiowska and Badowski [47], the application of herbicides with different modes of action (clomazone, metazachlor + quinmerac/clomazone) did not induce significant changes in the CF and TP content of WOSR seeds. Similar observations were made in the current study, where the tested weed control methods did not influence the content of basic nutrients in WOSR seeds. Adomas [18] demonstrated that the proportion of PUFAs in spring rapeseed oil was higher in treatments protected with foliar herbicides, compared with pre-emergent herbicides (328 vs. 311 g kg^{-1} DM), but no changes were found in the concentrations of SFAs or MUFAs. In the work of Mekki et al. [17], chemical weed control contributed to an increase in the content of palmitic acid (by 5%) and oleic acid (by 7%), and a decrease in the concentrations of linoleic acid (by 13%), linolenic acid (by 7%) and erucic acid (by 46%). In the current study, the method of herbicide application had no significant effect on the fatty acid profile of WOSR oil.

4.3. Growth Regulation

An analysis of the literature revealed that the application of growth regulators in autumn was weakly correlated with the nutrient content of WOSR seeds [16,19]. In a study by Jankowski [16], the application of tebuconazole or chlormequat chloride in autumn did not cause significant changes in the CF (431–437 vs. 441 g kg^{-1} DM) or TP (352 vs. 346–351 g kg^{-1} DM) content of WOSR seeds relative to control. Growth regulation in autumn also failed to modify the nutritional value of WOSR seeds in the work of Ijaz and Honermeier [19]. Similar observations were made in the present study, where the CF and TP content of WOSR seeds was not influenced by the application of growth regulators in autumn.

In most of the analyzed studies, growth regulation in spring did not affect the content of basic nutrients in WOSR seeds [16,19–23]. This is consistent with the results of the present study, where the application of growth regulators in spring did not induce changes in CF or TP levels in WOSR seeds. In contrast, Ijaz et al. [22] reported a significant increase in the TP content of WOSR seeds (approx. 3%) and no changes in CF levels in response to growth regulation in spring. The cited authors also found that the effect of this treatment on the fatty acid profile of oil varied across locations. The spring application of growth regulators significantly increased the concentrations of linoleic acid and linolenic acid in oil at Giessen but decreased the proportions of these two acids at Rauischholzhausen [22]. In the present study, growth regulation in spring did not modify the fatty acid profile of WOSR oil, irrespective of environmental or weather conditions.

4.4. Spring Nitrogen Fertilization

Spring N fertilization is a key agronomic factor that influences the quality of WOSR seeds. The CF content of seeds generally decreases with a rise in the N rate, and this reduction is exacerbated by delayed N fertilization. In turn, the TP content of seeds is negatively correlated with CF levels [1]. In studies conducted by Butkutė et al. [28], Jankowski [16], and Sieling et al. [32], WOSR seeds supplied with 160 kg N ha^{-1} accumulated 1–2% more CF than seeds fertilized with 240 kg N ha^{-1}. Dresbøll et al. [30] observed a clear drop (7%) in the CF content of seeds when the N rate was increased from 120 to 280 kg ha^{-1}. In turn, Varényiová and Ducsay [25] found no significant differences in the CF content of seeds between treatments fertilized with 160, 200, and 240 kg N ha^{-1}. According to Jankowski [1], higher N rates do not decrease the CF content of seeds only when they exert no yield-forming effects. In this study, WOSR seeds from treatments supplied with 160 and 200 kg N ha^{-1} in spring accumulated 2% more CF than seeds from treatments fertilized with the highest N rate (240 kg ha^{-1}). In the work of Butkutė et al. [28] and Jankowski [16], the TP content of seeds increased by 2–3% in response to the spring-applied N rate of 240 kg ha^{-1}. Dresbøll et al. [30] found that a very high N rate (280 kg ha^{-1}) induced a 26% increase in the TP content of WOSR seeds in comparison with the treatment fertilized with 120 kg N ha^{-1}. In turn, Ferguson et al. [31] did not report a significant increase in the TP content of seeds under the influence of rising N rates. In the present study, the TP content of WOSR seeds was higher by 8 g kg^{-1} DM (4%) in treatments supplied with the highest N rate (240 kg ha^{-1}) than in those fertilized with 160 kg N ha^{-1}.

4.5. Spring Sulfur Fertilization

Sulfur fertilization has different effects on the content of CF and TP in *Brassica* seeds. In a study by Sienkiewicz-Cholewa and Kieloch [33], the S rate of 60 kg ha^{-1} increased CF accumulation in WOSR seeds by 2%. According to Fazili et al. [34], S induced a significant (15%) increase in the CF content of oilseed crops (*Brassica campestris* L. and *Eruca sativa* Mill). In studies conducted in north-eastern Poland, S fertilization had a minor effect on CF and TP levels in *Brassicaceae* oilseeds [16,36–38,48]. In turn, Wielebski [35] found that an increase in the S rate from 0 to 60 kg ha^{-1} induced a minor, but significant decrease in CF accumulation (from 426 to 423 g kg^{-1} DM) and increased the TP content of WOSR seeds (from 207 to 210 g kg^{-1} DM). In the present study, CF and TP levels in WOSR seeds were not significantly modified by any of the tested S rates, which is consistent with the findings of Jankowski [16], Jankowski et al. [36], Jankowski et al. [37], and Groth et al. [38].

Sulfur fertilization compromises the quality of WOSR seeds by increasing their GLS content by 13–18% [35,37,39,49] to even 24–29% [16,38]. In the present study, S applied in spring increased GLS levels by 34%. The increase in GLS concentrations under the influence of S fertilization is attributed mainly to the intensified synthesis of alkenyl GLS [1,16,35,37–39,49]. This unfavorable process can compromise the feed value of fat-free seed residues used in the production of animal feed [37]. The S-induced increase in the concentration of alkenyl GLS ranged from 21–29% [16,37–39] to even 39% [present study, Table 3]. Alkenyl GLS levels increase under the influence of S fertilization mainly due to a rise in the concentrations of glucobrassicanapin (by 28%), gluconapin, and progoitrin (by 16–17%) [35]. In this study and experiments conducted by Wielebski [35], Malarz et al. [39], Ijaz and Honermeier [20], and Groth et al. [38], S fertilization had no effect on the fatty acid profile of WOSR oil.

5. Conclusions

Winter oilseed plants produced in the strip-till system accumulated the largest amounts of CF (498 g kg^{-1} DM). In turn, TP concentration in seeds was highest (196 g kg^{-1} DM) in conventional tillage and low-till systems. The seeds of WOSR plants grown in the conventional tillage system accumulated 0.5% less NDF, 0.4% more PUFAs (due to an increase in the proportion of linolenic acid), and 0.5–0.6% less MUFAs (due to a decrease in the proportion of oleic acid), compared with strip-till systems. The highest N rate (240 kg ha^{-1})

decreased the CF content (by 2%) and increased the TP content of seeds (by 4%). Sulfur fertilization increased GLS concentrations (mainly alkenyl GLS) by 34% without differentiating the content of basic nutrients. Sulfur fertilization induced an increase in the proportion of PUFAs (by 0.48%) and a decrease in the proportion of MUFAs (by 0.58%) in WOSR oil only in the season characterized by lower-than-average precipitation in spring and summer. The effect exerted by agronomic management on the quality of WOSR seeds was not influenced by the tillage system.

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