



Article

The Effects of Tillage Systems on the Management of Agronomic Factors in Winter Oilseed Rape Cultivation: A Case Study in North-Eastern Poland

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Abstract: The aim of this study was to analyze agronomic management in the production of winter oilseed rape (WOR) in different tillage systems. The field experiment (Poland, 2016–2019) had a 3⁵–1 fractional factorial design with two replications, where five fixed factors were tested at three levels. The experimental factors were as follows. 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 spring nitrogen (N) fertilizer: (D0) 160, (D1) 200, (D2) 240 kg ha^{−1}; E—rate of spring sulfur (S) fertilizer: (E0) 0, (E1) 40, (E2) 80 kg ha^{−1}. Seed yields were the highest in the strip-till system (5.95 Mg ha^{−1}). The effectiveness of weed control methods varied across different tillage systems. Foliar herbicides exerted the highest yield-forming effect in the strip-till system, pre-emergent and sequential herbicides were most effective in the low-till system, and pre-emergent herbicides were most effective in the conventional tillage system. Seed yields increased up to the N rate of 200 kg ha^{−1}. The highest N rate of 240 kg ha^{−1} was justified only when S was applied in spring. Sulfur significantly increased seed yields (by 17%). The results of the study indicate that low-till and strip-till systems can be viable alternatives to the conventional tillage system in WOR production.

Keywords: tillage; weed control; growth regulators; nitrogen and sulfur fertilization; seed yield



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1. Introduction

In 2016–2020, the average oilseed rape (*Brassica napus* L.) yields in the EU ranged from 1.4 (*Dfc*-Köppen climate classification) to 3.0–3.5 Mg ha^{−1} (*Dfb* and *Cfb*) [1]. Under favorable weather conditions, winter oilseed rape (WOR) yields can reach 5–6 Mg ha^{−1} in large commercial farms [2,3]. The yield potential of WOR is relatively weakly utilized in northern and central-eastern Europe [1]. In agricultural practice, the seed yield of WOR can be modeled by skillfully managing agronomic factors, including tillage, weed control, fertilization, and chemical growth regulation. In modern crop production, excessive tillage is being gradually replaced by simplified cultivation methods [4]. A combination of sustainable tillage techniques and sowing systems can increase the energy efficiency and productivity of WOR cultivation [5]. Various tillage systems can contribute to differences in weed infestation, which can strongly differentiate the yield potential of WOR. For this reason, the optimal weed control strategy should be selected for a given tillage system [4,6]. Tillage can influence the growth habit of oilseed rape plants [7,8]. Growing conditions that are highly favorable for the emergence and fall growth of WOR plants can contribute to excessive development of the leaf rosette, which can directly undermine successful overwintering. Chemical plant growth regulators have to be applied under such conditions.

By modifying the growth habit of plants, growth regulators can also influence yields [9]. The tillage system can also affect the content of mineral nitrogen (N) in soil [10,11]. Therefore, the optimal N rate can differ across various tillage systems, and it can also be determined by the availability of sulfur (S) in soil [11–13].

Tillage methods differ in the applied tools, fuel consumption, time required to prepare the seedbed, tillage depth, and management of crop residues after harvest [14–21]. Conventional tillage involving shallow plowing after harvest, pre-sowing tillage, and seedbed preparation is still the most popular soil cultivation method in Poland [22]. This method creates supportive conditions for the development of the root system, and it decreases pressure from weeds, diseases, and pests [23,24]. However, conventional tillage contributes to excessive drying of the soil surface layer [24] and increases the risk of water and wind erosion [23]. Conventional tillage can be replaced by low-till practices which loosen the soil without inverting it. Low-till methods reduce the number of tractor passes in the field, decrease farming inputs and energy consumption, are less dependent on weather conditions, promote water retention in soil, increase yields, and minimize soil erosion [16,22,25,26]. Modern cultivation skimmers work to a depth of 35 cm and promote root development in WOR production [20]. However, low-till practices are characterized by less effective management of crop residues and greater pressure from weeds (mainly annual monocotyledons in WOR cultivation), diseases, and pests. Strip-till is a fairly recent cultivation practice which loosens narrow strips of soil to a depth of 30–35 cm and enables simultaneous sowing and fertilization. This method is even less dependent on weather conditions, and it is characterized by higher effectiveness, lower agricultural inputs, and lower energy consumption than conventional tillage and low-till farming [26,27].

Weeds inhibit the development of WOR rosettes in fall, excessively increase terminal bud height [28], decrease seed yields [29], and compromise oilseed quality [22]. In WOR production, weeds are generally managed with pre-emergent herbicides (applied to the soil) to reduce the adverse effects of segetal vegetation already at the beginning of the growing season. Pre-emergent herbicides are effective in soils with satisfactory moisture content, but their effectiveness can be reduced in dry years [30]. Foliar herbicides applied after seedling emergence offer a good alternative in years with low precipitation. This treatment should be performed in the early stages of WOR growth, i.e., in the 2–4-leaves-unfolded stages (BBCH stages 12–14; Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [31]). Foliar herbicides are less effective when applied in the 4–8-leaves-unfolded stages (BBCH stages 14–18) because weeds have already established a strong root system and well-developed WOR rosettes may inhibit herbicide penetration into the stand [22,32]. According to Jankowski [21], sequential weed control is a more effective option in WOR production. In this approach, herbicides are applied twice in fall: once before seedling emergence (immediately after sowing) and once to the leaves (BBCH 12–14), to improve residual control of the key weed species remaining in the field after the previous herbicide treatment by selecting the active ingredient of a foliar herbicide. Previous research has shown that the growth rate of weeds and their species composition are significantly affected by tillage depth and the applied tillage method (soil mixing or inversion) [33,34]. According to Małacka-Jankowiak et al. [35], weed pressure is the lowest in conventional tillage systems and the highest in simplified tillage systems.

The growth of WOR plants can be strongly modified with the use of chemical growth regulators. These compounds can be applied in fall to inhibit the growth of rosettes (decrease terminal bud height, increase root collar diameter, and stimulate the development of the root system), which increases their winter hardiness, especially in early-sown WOR and during a prolonged fall growing season [36–39]. When applied in spring, growth regulators suppress the growth of the main stem and stimulate the formation of side shoots, thus minimizing the susceptibility to lodging and promoting greater sunlight interception by siliques on side shoots [22,38,40,41]. The spring application of growth regulators is particularly recommended under conditions that promote lodging (high N fertilization

levels, adequate water supply). Under such conditions, growth regulators can increase WOR yields by 10% [42].

Nitrogen and S fertilization is a key agricultural operation that enhances the yield potential and qualitative traits of WOR. Nitrogen and S affect the growth, development, and yield of WOR not only due to their direct influence on yield components [43–45], but also due to their antagonistic or synergistic effects on metabolism [46]. The efficiency of N fertilizers is determined by numerous factors, including the previous crop species, weather conditions, intensity of other agricultural inputs, and application timing [2,44,47,48]. For this reason, the optimal rate of N fertilizer application in spring may be difficult to determine.

The agronomic effectiveness of various tillage systems, weed control strategies, growth regulation methods, and mineral N and S fertilization regimes as individual factors in the production of WOR seeds has been extensively researched. Agronomic effectiveness has been evaluated in conventional field experiments (with one or two experimental factors) conducted in various climate zones. However, little is known about (i) the influence of the interactions between the main yield-forming and yield-protecting effects on WOR yields in a strip-till system; (ii) the influence of strip-till on the effectiveness of agronomic treatments in the production technology of WOR seeds; and (iii) the optimal levels of yield-forming and yield-protecting factors in various tillage systems. To fill in the existing knowledge gap, a three-year small-area field experiment was conducted to determine (i) the influence of various tillage systems, weed control strategies, growth regulation methods, and N and S fertilization on yield components (plants m^{-2} , siliques plant $^{-1}$, seeds silique $^{-1}$, 1000-seed weight) and seed yields in WOR production; (ii) the agronomic effectiveness of weed control, growth regulation, and N and S fertilization in different tillage systems (conventional tillage, low-till, and strip-till); and (iii) the direct effects of selected yield-forming (growth regulation, N and S fertilization) and yield-protecting (weed control) factors applied at three levels of intensity (low, medium, and high) in different tillage systems. The research hypotheses postulate that (i) the effectiveness of weed control and growth regulation is affected by the tillage system; (ii) the effectiveness of growth regulation is affected by N and S rates; (iii) N and S fertilization is a key determinant of WOR yields regardless of the tillage system; and (iv) S fertilization increases NFUE in both conventional and simplified (low-till, strip-till) tillage systems. In order to validate the research hypotheses and determine the effects of five agronomic factors on WOR yields, a 3^{5-1} fractional factorial design was applied. Such a design supports the assessment of the effects exerted by multiple agronomic factors and their interactions on the analyzed traits and parameters in a single field experiment (in classical field experiments, the number of variables is limited to two or three).

2. Materials and Methods

2.1. Field Experiment

A small-plot field experiment was conducted in 2016–2019 in the Agricultural Experiment Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, north-eastern Poland). The experiment had a 3^{5-1} fractional factorial design with five agronomic factors (A, B, C, D, and E) that were tested at three levels (0, 1, and 2) (Table 1). The main effects and two-factor interaction effects were evaluated with the use of modified fractional design generators [3,49].

The plot size at harvest was 15 m^2 (10 m by 1.5 m). In all years, WOR was grown after winter wheat as the preceding crop. Volunteer wheat was controlled by applying propaquizafop at 60 g ha^{-1} in all plots in BBCH stages 14–16. The experiment was established on Haplic Luvisol, underlain by boulder clay [50]. A detailed description of the research conditions (soil type and its chemical properties) is provided in the work by Szałkowski et al. [51] (Table S1). The technical specifications for tractors and farm machinery used in the experiment (make/type/model, engine power, working width, capacity, etc.) were given by Jankowski et al. [52].

Table 1. Experimental factors (2016–2019).

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)	Foliar (BBCH 12–14 [†])	sequential (0–2 days after sowing and BBCH 12–14)
C	Growth regulation ^{††}	none	one treatment (BBCH 14–15)	two treatments (BBCH 14–15 and 30–31)
D	Spring nitrogen rate (kg N ha ^{−1}) ^{†††}	160 (120 + 40) (BBCH 20 + 50)	200 (120 + 80) (BBCH 20 + 50)	240 (120 + 120) (BBCH 20 + 50)
E	Spring sulfur rate (kg S ha ^{−1}) ^{††††}	0	40 (BBCH 20)	80 (BBCH 20)

[†] Pre-emergent herbicides: 500 g ha^{−1} metazachlor, 500 g ha^{−1} dimethenamid-P, 250 g ha^{−1} quinmerac (0–2 days after sowing); foliar herbicides: 72 g ha^{−1} clopyralid, 24 g ha^{−1} picloram, 12 g ha^{−1} aminopyralid, 750 g ha^{−1} metazachlor (BBCH 12–14); sequential herbicides: 72 g ha^{−1} clomazone (0–2 days after sowing) and 72 g ha^{−1} clopyralid, 24 g ha^{−1} picloram, 12 g ha^{−1} aminopyralid (BBCH 12–14). ^{††} None: no growth regulation; one treatment: 210 g ha^{−1} mepiquat chloride and 30 g ha^{−1} metconazole (BBCH 14–15); two treatments: 210 g ha^{−1} mepiquat chloride and 30 g ha^{−1} metconazole (BBCH 14–15), and 125 g ha^{−1} difenoconazole and 62.5 g ha^{−1} paclobutrazol (BBCH 30–31). ^{†††} The first N rate was applied (BBCH 20–30) in the form of (i) ammonium nitrate (D0E0, D1E0, D2E0) or (ii) ammonium sulfate and ammonium nitrate (D0E1, D1E1, D2E1, D0E2, D1E2, D2E2). The second N rate was applied as ammonium sulfate (BBCH 50). ^{††††} Sulfur was applied as ammonium sulfate (BBCH 20–30). 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 [31].

The seeds of hybrid WOR cv. Kuga were sown at 50 germinating seeds per 1 m² between 13 and 23 August. Agronomic factors which were not used as experimental variables were applied in accordance with good agricultural practice. The winter oilseed rape was harvested in the fully ripe stage (8–24 July) with a small-plot harvester.

The weather conditions during the field experiment are shown in Figure 1. In the second and third year of the study, the mean daily temperature during the WOR growing season was higher than the long-term average by 1.3–1.7 °C. In year 1, mean daily temperature during the WOR growing season was comparable with the long-term average (7.9 °C). The total precipitation during the WOR growing season was 655 mm in 2016/2017, 707 mm in 2017/2018, and 468 mm in 2018/2019. The mean precipitation during the growing season in the study area over the last 37 years was 514 mm (Figure 1).

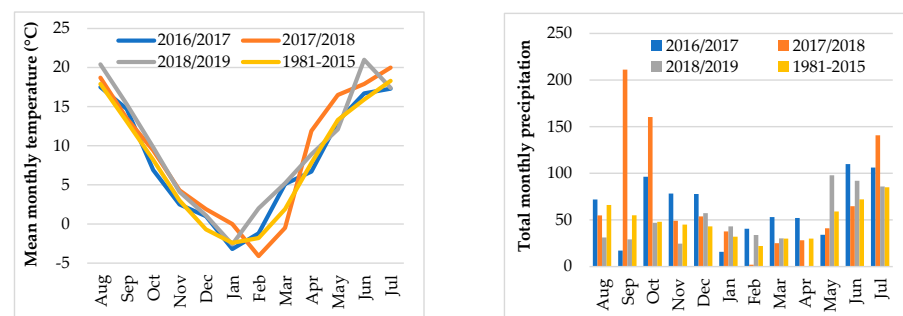


Figure 1. Weather conditions during the growing seasons of 2016–2019 vs. the long-term averages (1981–2015).

The fall growing season of WOR lasted 75 (year 1) to 95–97 days (years 2 and 3) (Table 2). Total precipitation was 8% below the long-term average only in the third year of the study. It should be noted that in year 2, total fall precipitation exceeded 400 mm, which significantly inhibited WOR development before winter dormancy. Winter dormancy lasted 121 to 140 days. Winter temperatures were relatively mild. In spring, total precipitation was the highest in year 1 (123% of the long-term average) and year 3 (100% of the long-term

average). In the second year, total precipitation in spring accounted for only 68% of the long-term average (Table 2).

Table 2. Phenological development of winter oilseed rape and weather conditions (2016–2019).

Parameter	Growing Season	Period			
		Fall Growth	Winter Dormancy	Spring Growth	Entire Growing Season
Number of days	2016/2017	75	140	120	335
	2017/2018	97	121	99	317
	2018/2019	95	129	109	333
	1981–2010	76	152	102	330
Total temperature (°C)	2016/2017	773	56	1548	2377
	2017/2018	978	−61	1544	2461
	2018/2019	1079	168	1504	2745
	1981–2010	865	−3	1360	2222
Mean daily temperature (°C)	2016/2017	10.3	0.4	12.9	8.2
	2017/2018	10.1	−0.5	15.6	7.8
	2018/2019	11.3	1.3	13.8	7.1
	1981–2010	11.4	0.0	13.3	6.7
Total precipitation (mm)	2016/2017	152	258	245	655
	2017/2018	419	153	135	707
	2018/2019	91	180	200	471
	1981–2010	143	171	200	514

2.2. Parameters Determined in the Field

Weed infestation of WOR stands was evaluated at the end of flowering (BBCH 69) in samples collected at two random locations (subplots) within 0.25 m² rings in each plot (the results were expressed per m²). The samples were analyzed to determine the species composition, fresh weight, and dry weight of the weeds. Standard measurements of yield components were conducted before WOR harvest (BBCH 82–85). The plant density per 1 m² was determined directly before WOR harvest at five random locations in each plot (1 m section of each of the two middle rows). The number of siliques plant^{−1} was counted in ten plants in each experimental treatment, and a sample of 20 siliques was collected from the two middle rows to determine the number of seeds silique^{−1}. The thousand-seed weight was determined after harvest and expressed on a 91%-dry-matter (DM) basis. The seed yield of WOR in each treatment was determined by weight after threshing and conversion to 91% DM.

2.3. Statistical Analysis

The yield components and seed yields were analyzed by ANOVA for a 3^{5−1} fractional factorial design with a resolution of V. The main effects of the fixed factors (A, B, C, D, and E) and all two-factor interactions (A × B, A × C, A × D, A × E, B × C, B × D, B × E, C × D, C × E, and D × E) during the three-year (Y) experiment (Y × A, Y × B, Y × C, Y × D, and Y × E) were evaluated. The above was achieved by eliminating higher-order interactions and incorporating them into the effect of statistical errors. The significance of differences between mean values was determined by Tukey's honest significant difference test at $p \leq 0.05$. All analyses were performed in the Statistica 13.3 program [53]. The *F*-values in ANOVA are presented in Table S2.

3. Results

3.1. Tillage

The weed species composition and diversity in different tillage systems are presented in Table S3. The mean values for the three-year study show that weed infestation levels (expressed as both fresh weight and dry weight of weeds) were highest in the low-till system. The fresh and dry weight of weeds were 2- to 4-fold lower in strip-till and conventional tillage systems, respectively, compared with the low-till system (Table S4).

The plant density after harvest was the highest in the conventional tillage system (28 plants m^{-2}); it was somewhat lower (by 3%) in the low-till system, and the lowest (by 10%) in the strip-till system (Table 3). In year 1, the plant density before harvest was 7% and 30% higher in the conventional tillage system than in the low-till and strip-till systems, respectively. In the growing season with the most favorable conditions for seedling emergence (year 2), the plant density before harvest was the highest (30–31 m^{-2}) in the strip-till and conventional tillage systems. In turn, in the growing season with the least favorable moisture conditions after sowing (year 3), the plant density before harvest was the highest (25 m^{-2}) in the low-till system (Figure 2).

Table 3. Yield components in the production of winter oilseed rape seeds (across years).

Agronomic Factor	Level	Plants m^{-2}	Siliques $Plant^{-1}$	Seeds $Siliques^{-1}$	1000-Seed Weight (g)
Tillage	strip-till	25 ^c	196 ^a	26.3 ^a	5.18 ^b
	low-till	27 ^b	180 ^b	25.8 ^b	5.28 ^a
	conventional tillage	28 ^a	183 ^b	25.6 ^b	5.29 ^a
Weed control	pre-emergent	27	190	25.9	5.17 ^b
	foliar	26	185	26	5.30 ^a
	sequential	27	184	25.8	5.29 ^a
Growth regulation	none	26.5	186.6	26.1	5.23
	BBCH 14–15	26.4	186.7	25.7	5.29
	BBCH 14–15 and 30–31	26.6	186.2	25.8	5.23
Spring nitrogen rate (kg N ha^{-1})	160	27	180 ^b	25.9	5.20 ^b
	200	26	191 ^a	25.9	5.23 ^b
	240	27	189 ^a	25.8	5.32 ^a
Spring sulfur rate (kg S ha^{-1})	0	27	174 ^b	25.6	5.40 ^a
	40	26	194 ^a	25.9	5.19 ^b
	80	26	192 ^a	26.1	5.17 ^b

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

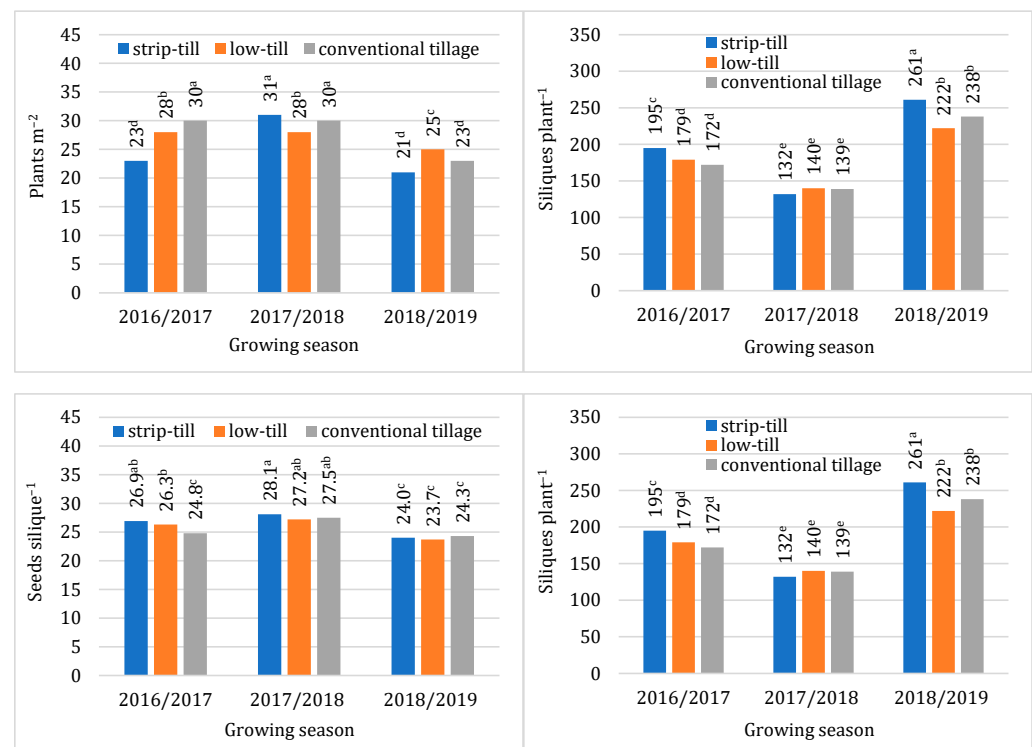


Figure 2. The effect of tillage system on seed-yield components in winter oilseed rape production across years (Y $\times$ B). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

On average, WOR plants grown in the strip-till system produced the highest number of siliques plant⁻¹ (196) during the entire three-year study (Table 3). This yield component was influenced by the interactions between weather conditions across years and the tillage system ($Y \times A$) (Table S1). In years 1 and 3, the number of siliques plant⁻¹ was the highest in the strip-till system (195 and 261, respectively), and it was 8–15% and 9–12% lower in the low-till and conventional tillage systems, respectively. In year 2, the number of siliques plant⁻¹ did not differ between the examined tillage systems (Figure 2).

The strip-till system also promoted silique filling (26 seeds silique⁻¹) (Table 3). Winter oilseed plants grown in the strip-till system were characterized by a very high number of seeds silique⁻¹ in the first and second years of the study (27 and 28, respectively) (Figure 2).

Winter oilseed plants grown in conventional tillage and low-till systems produced seeds with similar 1000-seed weights (5.28–5.29 g). The seed weight was lower in the strip-till system (5.18 g), which could be attributed to the highest number of siliques plant⁻¹ and seeds silique⁻¹ in this treatment (Table 3).

The effects of different tillage systems on the 1000-seed weight were influenced by weather conditions in each year of the study ($Y \times A$) (Table S1). In years 1 and 2, the 1000-seed weight was the highest (5.00 g and 5.80 g, respectively) in the conventional tillage system. In year 3, the heaviest seeds (5.26 g) were noted in the low-till system (Figure 2). It should be stressed that the effects of different tillage systems on the 1000-seed weight were modified by the applied weed control method ($A \times B$) (Table S1). In strip-till and conventional tillage systems, foliar herbicides induced the greatest increase in the 1000-seed weight. In the low-till system, WOR seeds were the heaviest in treatments with sequential weed control (pre-emergent and foliar herbicides) (Table 4).

Table 4. The effect of tillage system and weed control ($A \times B$) on 1000-seed weight (g) in winter oilseed rape production (across years).

Weed Control	Tillage System		
	Strip-Till	Low-Till	Strip-Till
Pre-emergent	5.15 ^c	5.19 ^{bc}	5.19 ^{bc}
Foliar	5.24 ^b	5.27 ^b	5.38 ^a
Sequential	5.16 ^c	5.37 ^a	5.32 ^{ab}

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The winter oilseed rape yields were very high (5.45–6.13 Mg ha⁻¹) (Table 5). On average, seed yields were the highest in the strip-till system (5.95 Mg ha⁻¹), and they were 50 and 140 kg ha⁻¹ lower in the low-till and conventional tillage systems, respectively. In each year of the experiment, the highest seed yields were noted in a different tillage system. In year 1, WOR yields peaked in the strip-till system (6.13 Mg ha⁻¹), 240 and 300 kg ha⁻¹ higher than in the low-till and conventional tillage systems, respectively. In year 2, seed yields were the highest in the conventional tillage system (5.92 Mg ha⁻¹), average in the strip-till system (5.79 Mg ha⁻¹), and the lowest in the low-till system (5.45 Mg ha⁻¹). In year 3, the low-till system was characterized by the highest seed yields (6.10 Mg ha⁻¹), and WOR yields were around 150–170 kg ha⁻¹ lower in the remaining tillage systems (Table 5). The effect of the tillage system on WOR yields was modified by the spring-applied S rate ($A \times E$) (Table S1). The absence of S fertilization induced a greater decrease in seed yields in the low-till system than in the strip-till and conventional tillage systems (13% vs. 8–9%). When S was incorporated into the fertilization regime of WOR, the tillage system had no significant effect on seed yields (Table 6).

Table 5. The effect of tillage system on seed yields (Mg ha^{-1}) in winter oilseed rape production across years ($Y \times A$).

Growing Season	Tillage System		
	Strip-Till	Low-Till	Conventional Tillage
2016/2017	6.13 ^a	5.89 ^{ab}	5.83 ^b
2017/2018	5.79 ^b	5.45 ^c	5.92 ^{ab}
2018/2019	5.93 ^{ab}	6.10 ^a	5.95 ^{ab}
Mean	5.95 ^a	5.81 ^b	5.90 ^{ab}

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Table 6. The effect of tillage system and the spring sulfur rate ($A \times E$) on seed yields (Mg ha^{-1}) in winter oilseed rape production across years.

Spring Sulfur Rate (kg S ha^{-1})	Tillage System		
	Strip-Till	Low-Till	Conventional Tillage
0	5.62 ^b	5.27 ^c	5.56 ^b
40	6.12 ^a	6.12 ^a	6.03 ^a
80	6.12 ^a	6.05 ^a	6.12 ^a

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

3.2. Weed Control

The weed species composition and diversity in treatments with different weed control methods are presented in Table S5. The fresh weight (66 g m^{-2}) and dry weight (14 g m^{-2}) of weeds were highest after the application of pre-emergent herbicides. Foliar and sequential herbicides decreased the fresh weight and dry weight of weeds by 27% and 31%, respectively (Table S6).

Pre-emergent herbicides decreased the 1000-seed weight (by 2% on average) in WOR plants relative to the remaining weed control methods (Table 3). However, pre-emergent weed control exerted a negative effect on the 1000-seed weight only in year 2. In the remaining years of the study, the applied weed control methods did not induce differences in the 1000-seed weight of WOR plants (Table 7).

Table 7. The effect of weed control on 1000-seed weight (g) in winter oilseed rape production across years ($Y \times B$).

Growing Season	Weed Control		
	Pre-Emergent	Foliar	Sequential
2016/2017	4.84 ^d	4.85 ^d	4.95 ^d
2017/2018	5.56 ^b	5.87 ^a	5.74 ^a
2018/2019	5.12 ^c	5.17 ^c	5.17 ^c

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The influence of the applied weed control methods on the WOR yields was significantly differentiated by precipitation and temperature (Table S1). In year 1, seed yields were significantly higher (6.01 Mg ha^{-1}) in treatments with foliar herbicides, and they were around $80\text{--}90 \text{ kg ha}^{-1}$ higher than in treatments with pre-emergent and sequential herbicides. In year 2, pre-emergent weed control induced the greatest increase in WOR yields. In year 3, seed yields were not significantly differentiated by any of the examined weed control methods. However, on average, all herbicide treatments exerted similar protective effects on seed yields during the entire experiment (Table 8). The protective effects of weed control were significantly modified by the tillage system ($A \times B$) (Table S1). In the strip-till system, WOR yields were higher (6.06 Mg ha^{-1}) after the application of foliar herbicides. In contrast, foliar herbicides were least effective in increasing seed yields

in the low-till system (5.72 Mg ha^{-1}). In the conventional tillage system, pre-emergent herbicides contributed to the greatest increase in seed yields (6.00 Mg ha^{-1}) (Table 9).

Table 8. The effect of weed control on seed yields (Mg ha^{-1}) in winter oilseed rape production across years ($Y \times B$).

Growing Season	Weed Control		
	Pre-Emergent	Foliar	Sequential
2016/2017	5.93 ^{ab}	6.01 ^a	5.92 ^{ab}
2017/2018	5.86 ^{ab}	5.54 ^c	5.75 ^b
2018/2019	5.97 ^a	5.98 ^a	6.04 ^a
Mean	5.92	5.85	5.90

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Table 9. The effect of tillage system and weed control ($A \times B$) on seed yields (Mg ha^{-1}) in winter oilseed rape production across years.

Weed Control	Tillage System		
	Strip-Till	Low-Till	Conventional Tillage
Pre-emergent	5.87 ^b	5.88 ^b	6.00 ^{ab}
Foliar	6.06 ^a	5.72 ^c	5.75 ^{bc}
Sequential	5.93 ^b	5.83 ^b	5.95 ^b

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

3.3. Growth Regulation

The statistical analysis did not reveal significant differences in yield components under the influence of growth regulators, regardless of weather conditions across years ($Y \times C$) or the intensity of the remaining agronomic practices ($A \times C$, $B \times C$, $C \times D$, $C \times E$) (Tables S1 and S7).

None of the tested growth regulator treatments exerted yield-forming effects. Seed yields were not influenced by the interactions between growth regulators and weather conditions ($Y \times C$) or the intensity of the remaining agronomic factors ($A \times C$, $B \times C$, $C \times D$, $C \times E$) (Tables S1 and S7).

3.4. Spring Nitrogen Fertilization

Nitrogen fertilization in spring (160 , 200 , 240 kg ha^{-1}) significantly differentiated the number of siliques plant^{-1} and the 1000-seed weight (Table S1). An increase in the spring-applied N rate from 160 to 200 kg ha^{-1} increased the number of siliques plant^{-1} by around 5%. This yield component was not affected by a further increase in N rates (up to 240 kg ha^{-1}) (Table 3). The N rate of 200 kg ha^{-1} promoted silique formation only in year 1 (the number of siliques plant^{-1} increased by 17%). In the remaining years of the study, N rates did not modify the number of siliques plant^{-1} (Table 10).

Table 10. The effect of the spring nitrogen rate on the number of siliques plant^{-1} in winter oilseed rape production across years ($Y \times D$).

Growing Season	Spring Nitrogen Rate (kg N ha^{-1})		
	160	200	240
2016/2017	165 ^c	193 ^b	188 ^b
2017/2018	136 ^d	137 ^d	138 ^d
2018/2019	239 ^a	242 ^a	240 ^a

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The highest N rate (240 kg ha^{-1}) induced a minor, but significant, increase (0.09 – 0.12 g) in the 1000-seed weight (Table 3). The relationship between the N rate and the 1000-seed

weight was not affected by weather conditions across years ($Y \times D$) or the intensity of the remaining agronomic practices ($A \times D$, $B \times D$, $C \times D$, $D \times E$) (Tables S1 and S7).

The yield-forming effects of N fertilization were strongly modified by weather conditions ($Y \times D$) and S fertilization ($D \times E$) (Table S1). In the first year of the study (with optimal precipitation in spring), an increase in the N rate from 160 to 200 and 240 kg ha⁻¹ increased seed yields by 7% and 9%, respectively. In years 2 and 3 (when rainfall distribution was less favorable in spring), seed yields did not increase by more than 4% in response to N rates of 200 and 240 kg ha⁻¹ (Table 11). In treatments not supplied with S, WOR yields continued to increase up to the N rate of 200 kg N ha⁻¹. The yield-forming effects of the highest N rate (240 kg ha⁻¹) were apparent only in treatments fertilized with the minimum 40 kg S ha⁻¹ (Table 12).

Table 11. The effect of the spring nitrogen rate on seed yields (Mg ha⁻¹) in winter oilseed rape production across years ($Y \times D$).

Growing Season	Spring Nitrogen Rate (kg N ha ⁻¹)		
	160	200	240
2016/2017	5.66 ^{bc}	6.03 ^{ab}	6.17 ^a
2017/2018	5.57 ^c	5.76 ^{bc}	5.82 ^b
2018/2019	5.89 ^b	6.02 ^{ab}	6.07 ^{ab}
Mean	5.71 ^b	5.94 ^a	6.02 ^a

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Table 12. The effect of spring nitrogen and sulfur rates ($D \times E$) on seed yields (Mg ha⁻¹) in winter oilseed rape production across years.

Spring Sulfur Rate (kg S ha ⁻¹)	Spring Nitrogen Rate (kg N ha ⁻¹)		
	160	200	240
0	5.45 ^d	5.53 ^c	5.46 ^d
40	5.90 ^b	6.10 ^{ab}	6.26 ^a
80	5.78 ^{bc}	6.18 ^{ab}	6.33 ^a

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

3.5. Spring Sulfur Fertilization

Sulfur fertilization in spring (0, 40, 80 kg ha⁻¹) exerted a significant influence on the number of siliques plant⁻¹ and the 1000-seed weight (Table S1). In treatments fertilized with ≥ 40 kg S ha⁻¹, the number of siliques plant⁻¹ increased by around 11% relative to treatments where S was not applied (Table 3). The relationship between S fertilization and the number of siliques plant⁻¹ was not affected by weather conditions across years ($Y \times D$) or the intensity of the remaining agronomic factors ($A \times E$, $B \times E$, $C \times E$, $D \times E$) (Tables S1 and S7).

Sulfur fertilization decreased the 1000-seed weight by 4% on average (Table 3). An adverse effect of S fertilization was observed only in the second year of the study, when the application of this macronutrient decreased the 1000-seed weight by up to 8–9% (Table 13).

Table 13. The effect of the spring sulfur rate on 1000-seed weight (g) in winter oilseed rape production across years ($Y \times E$).

Growing Season	Spring Sulfur Rate (kg S ha ⁻¹)		
	0	40	80
2016/2017	4.94 ^d	4.84 ^d	4.86 ^d
2017/2018	6.06 ^a	5.58 ^b	5.53 ^b
2018/2019	5.18 ^c	5.16 ^c	5.11 ^c

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Sulfur fertilization in spring exerted considerable yield-forming effects. During the entire three-year study, seed yields increased by 11% (610–620 kg ha^{−1}) on average in response to S rates of 40 or 80 kg S ha^{−1} (Table 14). Sulfur fertilization was particularly effective in increasing seed yields in the first and second years of the study when precipitation levels were high in the fall growing season (approx. 150 and 420 mm, respectively). In these years, S fertilization (40 or 80 kg ha^{−1}) increased WOR yields by 800–900 kg ha^{−1} (15–17%). The yield-forming effects of S fertilization were much lower in year 3, when seed yields increased by only 140 kg ha^{−1} (2%) (Table 14). The above could be attributed to low precipitation (91 mm) in fall and, consequently, weaker S leaching (Table 2).

Table 14. The effect of the spring sulfur rate on seed yields (Mg ha^{−1}) in winter oilseed rape production across years (Y × E).

Growing Season	Spring Sulfur Rate (kg S ha ^{−1})		
	0	40	80
2016/2017	5.37 ^d	6.22 ^{ab}	6.27 ^a
2017/2018	5.15 ^d	6.05 ^b	5.95 ^c
2018/2019	5.93 ^c	5.99 ^{bc}	6.07 ^b
Mean	5.48 ^b	6.09 ^a	6.10 ^a

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

4. Discussion

4.1. Tillage

According to Jankowski [22], high and stable WOR yields can be achieved only by deep plowing, regardless of the applied tools. In a study by Kováč et al. [17], WOR yields were around 0.2 Mg ha^{−1} lower on average in the low-till system than in the conventional tillage system. In the work of Jaskulska et al. [18], plowless tillage to a depth of 8–10 cm, followed by deep aeration (18–20 cm) with a stubble cultivator, decreased yields by around 0.3 Mg ha^{−1} in comparison with conventional tillage. In turn, in treatments where tillage was limited to stubble disking only (to a depth of 8–10 cm), yields decreased by 0.6 Mg ha^{−1} [18]. Different results were reported by Katai [15] in a field experiment conducted in Hungary. Pre-sowing tillage with a field cultivator induced a greater increase in WOR yields than conventional plowing (3.5 vs. 3.0 Mg ha^{−1}). Strip-till is becoming increasingly popular in agricultural production, in particular in large commercial farms [26,54,55]. Shah et al. [19] demonstrated that WOR yields were around 4% higher in strip-till than in low-till systems. In the work of Jaskulska and Jaskulski [21], WOR yields were around 11% higher in strip-till than in conventional tillage systems. In the current study, seed yields reached 5.95 Mg ha^{−1} in the strip-till system, and they were lower in conventional tillage (by 1%) and low-till systems (by 3%). Due to varied weather conditions during the experiment, the highest WOR yields were noted in different tillage systems in each year of the study: in year 1 in the strip-till system, in year 2 in the conventional tillage system, and in year 3 in the low-till system.

4.2. Weed Control

According to Franek [56], Hamzei et al. [32], and Pacanoski [30], the timing of herbicide application can induce significant differences in WOR yields. In the work of Hamzei et al. [32], WOR yields peaked (5.5 Mg ha^{−1}) when herbicides were applied during seedling emergence. Weed control treatments in BBCH stages 14 or 18 decreased seed yields by 7% and 16%, respectively. In turn, Pacanoski [30] reported that weeds were more effectively controlled when herbicides (dimethachlor or metazachlor) were applied in BBCH stage 14 than before emergence. This observation was attributed to low soil moisture content directly after sowing, when seed yields were 9% higher in treatments protected with foliar herbicides than pre-emergent herbicides. Franek [56] noted the highest seed yields after the application of foliar herbicides in BBCH stages 11–12. Pre-emergent or foliar herbicides

applied in BBCH stages 14–16 decreased seed yields by 4% and 13%, respectively. In the present study, the yield-forming effect of chemical weed control was influenced by the weather conditions and tillage system. In year 1, seed yields were higher (6.0 Mg ha^{-1}) after the application of foliar herbicides, and were around 2% lower in the remaining weed control treatments. In year 2, pre-emergent herbicides led to the greatest increase in WOR yields (5.9 Mg ha^{-1}), whereas sequential and foliar herbicides decreased seed yields by 2% and 6%, respectively. In year 3, the analyzed weed control methods did not significantly affect seed yields. Weeds were most effectively controlled by foliar herbicides in the strip-till system, by pre-emergent or sequential herbicides in the low-till system, and by pre-emergent herbicides in the conventional tillage system.

4.3. Growth Regulation

Growth regulators are applied in fall to inhibit shoot elongation and stimulate the development of the root system [22]. In a study conducted in Lithuania (*Cfb*-Köppen climate classification), the application of growth regulators in fall increased WOR yields by 15–20%, mainly due to a higher number of siliques plant⁻¹ [57]. In western Germany (*Cfc*), WOR yields increased by 13% when metconazole was applied in fall. Tebuconazole and trinexapac-ethyl applied in fall were less effective and increased seed yields by only 7% [58]. In turn, in a study conducted by Jankowski [59] in north-eastern Poland (*Cfb*), tebuconazole applied in BBCH stage 14 did not induce significant differences in WOR yields relative to the control. A chlormequat chloride treatment applied in fall decreased WOR yields by 5%. In the present study, the application of growth regulators in fall had no positive effect on WOR yields either.

Growth regulators are applied in spring to reduce the risk of lodging, suppress *P. lingam* infections [22,38,40,41,60], and stimulate the development of side shoots in WOR plants [22]. In the experiments conducted by Matysiak et al. [60] and Matysiak and Kaczmarek [40], spring-applied growth regulators increased WOR yields. The highest increase in seed yields was observed after the spring application of tebuconazole (14–17%) [40,60], followed by chlormequat chloride (9%) [60], and chlorocholine chloride (5%) [40]. Kuai et al. [41] also reported a significant increase in WOR yields (by 33%) in response to paclobutrazol applied in the stem elongation stage. Miliuviene et al. [57] and Ijaz and Honermeier [61] demonstrated that the application of growth regulators in spring promoted silique formation, increased seed weight, and increased yields by 9% [61] to 22% [57]. In the work of Jankowski [59] and Ijaz and Honermeier [62], seed yields increased by only 2% in response to a mixture of difenoconazole and paclobutrazol. In turn, Jankowski [59] found that chlormequat chloride applied in spring at 675 g ha^{-1} was not productive, whereas a higher dose (1012.5 g ha^{-1}) decreased seed yields by 3%. In Germany, two growth regulator treatments (in fall and spring) increased WOR yields by 5–10% [38]. The reported increase in yields was attributed mainly to the fact that the fall treatment contributed to the overwintering success of WOR plants. In the current study, two growth regulator treatments (BBCH 14–15 and 30–31) did not improve WOR yields.

4.4. Spring Nitrogen Fertilization

The optimal spring-applied N rate is difficult to determine in WOR production due to the presence of numerous interactions between the studied variables, including weather conditions, agricultural input intensity, previous crop, form of the N fertilizer, and application date [22]. Research has shown that N rates of $150\text{--}180 \text{ kg N ha}^{-1}$ are most productive in a medium-input production technology of WOR. In high-input production technologies, the optimal rate of N fertilizer has been determined to be $180\text{--}200 \text{ kg N ha}^{-1}$ [63–65] or even 240 kg N ha^{-1} [1,22,48]. In a study by Varényiová and Ducsay [65], WOR yields peaked in response to 200 kg N ha^{-1} , whereas N rates of 160 and 240 kg N ha^{-1} decreased seed yields by 5% and 15%, respectively. Nitrogen rates higher than 200 kg N ha^{-1} also failed to improve crop yields in the work of Butkutė et al. [63], White et al. [64], and Groth et al. [43]. In contrast, Litke et al. [48] reported the highest WOR yields in response to

an N rate of 240 kg N ha⁻¹, whereas a decrease in the N rate to 180 kg ha⁻¹ reduced seed yields by 7%. Similar results were obtained by Jankowski [59]—WOR yields reached 4.9 Mg ha⁻¹ in treatments supplied with 240 kg N ha⁻¹ but decreased by 6% when the N rate was reduced to 160 kg ha⁻¹. The present study demonstrated that in north-eastern Poland, high WOR yields (5.7 Mg ha⁻¹) can be achieved by applying N fertilizer at a rate of 160 kg ha⁻¹. However, the yield potential of WOR was maximized in response to an N rate of 200 kg N ha⁻¹ (seed yields increased by approx. 4%), and similar results were reported by Varényiová and Ducsay [65].

Numerous researchers have demonstrated that the effectiveness of N fertilization (in particular at high N rates) in the production of *Brassica* plants is enhanced when crops are adequately supplied with S [43,49,66,67]. Wielebski et al. [66] found that in treatments fertilized with 220 kg N ha⁻¹, the application of 60 kg S ha⁻¹ increased WOR yields by around 8%. In a study by Jankowski [59], the highest N rate (240 kg ha⁻¹) increased yields only when combined with an S rate of 30 kg ha⁻¹ applied in early spring. Balanced N and S fertilization also increases yields in other *Brassica* crops [49,67,68]. In the current study, the highest N rate (240 kg ha⁻¹) exerted a yield-forming effect only after the application of 40 kg S ha⁻¹ in early spring.

4.5. Spring Sulfur Fertilization

In the production of oilseed crops of the family *Brassicaceae*, the yield-forming effects of S fertilization are usually more apparent in soils that are deficient in this nutrient [69–72]. In north-eastern Poland, S fertilization increased the yields of oilseed crops (WOR, spring oilseed rape, white mustard, Indian mustard, camelina, crambe) by 4–8% [43] and even up to 22% [49]. In a study by Sienkiewicz-Cholewa and Kieloch [71], spring-applied S rates of 40–60 kg ha⁻¹ increased WOR yields by 13–15%. Groth et al. [43] reported a 3–4% increase in WOR yields in response to an S rate of 40 kg S ha⁻¹. In turn, Wielebski et al. [66] found that 30 kg S ha⁻¹ was the most effective S rate in WOR production (seed yields increased by 5%), whereas 60 kg S ha⁻¹ did not induce a further increase in yields. In the present study, the greatest increase in seed yields (11%) was observed in treatments fertilized with 40 kg S ha⁻¹. Sulfur fertilization was particularly effective (seed yields increased by 17%) in years with high precipitation in fall and winter (years 1 and 2).

5. Conclusions

An analysis of the mean values for the three-year study revealed that seed yields were highest in the strip-till system (5.95 Mg ha⁻¹), and they were 50 and 140 kg ha⁻¹ lower in the conventional tillage and low-till systems, respectively. In the strip-till system, WOR produced 8% and 2% more siliques plant⁻¹ and seeds silique⁻¹, respectively. Weed control exerted the highest yield-forming effect when herbicides were applied in BBCH stages 12–14 in the strip-till system (6.06 Mg ha⁻¹), before emergence or sequentially in the low-till system (5.72 Mg ha⁻¹), and directly after sowing in the conventional tillage system (6.00 Mg ha⁻¹). Growth regulators did not increase seed yields in any of the examined tillage systems, regardless of weather conditions. Weed control and N and S fertilization had no influence on the yield-forming effects of growth regulators. Spring N fertilization increased seed yields up to a rate of 200 kg ha⁻¹ (5.94 Mg ha⁻¹). Nitrogen fertilization improved seed yields by increasing the number of siliques plant⁻¹ and the 1000-seed weight (by 6% and 2%, respectively). The highest N rate of 240 kg ha⁻¹ was justified only when combined with an S rate of 40 kg ha⁻¹ applied in early spring (seed yield increased by 0.36 Mg ha⁻¹). The effect of N fertilization on WOR yields was not influenced by the tillage system. The S rate of 40 kg ha⁻¹ significantly increased seed yields (by 0.85–0.90 Mg ha⁻¹), in particular in years with high precipitation in fall (the number of siliques plant⁻¹ and the 1000-seed weight increased by 11% and 4%, respectively). The absence of S fertilization led to a greater decrease in seed yields in the low-till system.

The present study demonstrated that the strip-till system exerts strong yield-forming effects in WOR production. In north-eastern Poland, weed control and S fertilization

methods in the strip-till system have to be adjusted to local conditions. The study also revealed that regardless of the tillage system, S should be incorporated in the N fertilization regime, in particular when N is applied at a rate of $>200 \text{ kg ha}^{-1}$. The yield-forming effects of the remaining agronomic factors (growth regulation and the rate of spring N fertilizer) were independent of the tillage system (conventional tillage, low-till, and strip-till). The results of this study indicate that future research on the yield-forming effect of the strip-till system in WOR cultivation should focus on developing effective weed control methods and S fertilization. The effects of tillage systems on the management of these agronomic factors should be evaluated under different agroecological conditions (preceding crop, post-harvest residue management, soil compactness, soil nutrient content, etc.).

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14030437/s1>, Table S1: Chemical properties of the analyzed soil; Table S2: F-test statistics in ANOVA of yield components and seed yield in WOR production; Table S3: Number of weeds per m^2 in WOR stands at the end of flowering (BBCH 69) in different tillage systems (across years); Table S4: Weed weight in WOR stands at the end of flowering (BBCH 69) in different tillage systems (mean of three years); Table S5: Number of weeds per m^2 in WOR stands at the end of flowering (BBCH 69) in treatments with different weed control methods (across years); Table S6: Weed weight in WOR stands at the end of flowering (BBCH 69) in treatments with different weed control methods (mean of three years); Table S7: Yield components and seed yields in WOR production.

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References

1. Faostat. Food and Agriculture Organization Corporate Statistical Database. Available online: <http://www.apps.fao.org> (accessed on 28 October 2023).
2. Rathke, G.W.; Christen, O.; Diepenbrock, W. Effects of nitrogen source and rate on productivity and quality of winter oilseed rape (*Brassica napus* L.) grown in different crop rotations. *Field Crops Res.* **2005**, *94*, 103–113. [\[CrossRef\]](#)
3. Jankowski, K.J.; Budzyński, W.S.; Załuski, D.; Hulanicki, P.S.; Dubis, B. Using a fractional factorial design to evaluate the effect of the intensity of agronomic practices on the yield of different winter oilseed rape morphotypes. *Field Crops Res.* **2016**, *188*, 50–61. [\[CrossRef\]](#)
4. Rieger, S.; Richner, W.; Streit, B.; Frossard, E.; Liedgens, M. Growth, yield, and yield components of winter wheat and the effects of tillage intensity, preceding crops, and N fertilization. *Eur. J. Agron.* **2008**, *28*, 405–411. [\[CrossRef\]](#)

5. Saldukaitė, L.; Šarauskis, E.; Zabrodskiy, A.; Adamavičienė, A.; Buragienė, S.; Kriaučiūnienė, Z.; Savickas, D. Assessment of energy saving and GHG reduction of winter oilseed rape production using sustainable strip tillage and direct sowing in three tillage technologies. *Sustain. Energy Technol. Assess.* **2022**, *51*, 101911. [\[CrossRef\]](#)
6. Bleharczyk, A.; Małecka, I.; Sawińska, Z.; Waniorek, B. Effect of tillage system on weed infestation in 3-year crop rotation. *Prog. Plant Prot.* **2011**, *51*, 827–831. (In Polish)
7. Jaskulska, I.; Gałęzewski, L.; Piekarczyk, M.; Jaskulski, D. Strip-till technology-a method for uniformity in the emergence and plant growth of winter rapeseed (*Brassica napus* L.) in different environmental conditions of Northern Poland. *Ital. J. Agron.* **2018**, *3*, 194–199. [\[CrossRef\]](#)
8. Gawęda, D.; Haliniarz, M. The Yield and weed infestation of winter oilseed rape (*Brassica napus* L. ssp. *oleifera* Metzg) in two tillage systems. *Agriculture* **2022**, *12*, 563. [\[CrossRef\]](#)
9. Bečka, D.; Vasak, J.; Kroutil, P.; Stranc, P. Autumn growth and development of different winter oilseed rape variety types at three input levels. *Plant Soil Environ.* **2004**, *4*, 168–174. [\[CrossRef\]](#)
10. Lickfett, T. Effects of reduced tillage intensity on soil N_{min} dynamics following oilseed rape cultivation. In *Plant Nutrition: Food Security and Sustainability of Agro-Ecosystems through Basic and Applied Research*; Horst, W.J., Ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2001; pp. 872–873.
11. Montemurro, F. Different nitrogen fertilization sources, soil tillage, and crop rotations in winter wheat: Effect on yield, quality, and nitrogen utilization. *J. Plant Nutr.* **2009**, *32*, 1–18. [\[CrossRef\]](#)
12. Hansen, E.M.; Munkholm, L.J.; Olesen, J.E. N-utilization in non-inversion tillage systems. *Soil Tillage Res.* **2011**, *113*, 55–60. [\[CrossRef\]](#)
13. Brennan, J.; Hackett, R.; McCabe, T.; Grant, J.; Fortune, R.A.; Forristal, P.D. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. *Eur. J. Agron.* **2014**, *54*, 61–69. [\[CrossRef\]](#)
14. Fuentes, M.; Govaerts, B.; De Leon, F.; Hidalgo, C.; Dendooven, L.; Sayre, K.D.; Etchevers, J. Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. *Eur. J. Agron.* **2009**, *30*, 228–237. [\[CrossRef\]](#)
15. Katai, Z. Soil tillage systems as an abiotic factor in the production of oilseed rape (*Brassica napus* L.). *Cereal Res. Commun.* **2009**, *37*, 411–414.
16. Morris, N.L.; Miller, P.C.H.; Orson, J.H.; Froud-Williams, R.J. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. *Soil Tillage Res.* **2010**, *108*, 1–15. [\[CrossRef\]](#)
17. Kováč, L.; Jakubová, J.; Kotorová, D. The cost and the economic effectiveness analysis of the winter rape production technologies (*Brassica napus* L. ssp. *oleiferera*) on heavy soils. *Agriculture* **2011**, *57*, 154–165. [\[CrossRef\]](#)
18. Jaskulska, I.; Jaskulski, D.; Kotwica, K.; Piekarczyk, M.; Wasilewski, P. Yielding of winter rapeseed depending on the forecrops and soil tillage methods. *Ann. Univ. Mariae Curie-Skłodowska Sect. E Agric.* **2014**, *69*, 30–38. (In Polish)
19. Shah, S.; Flint, C.; Langton, D.; Fletcher, J.M. Effect of different cultivation systems, seed rate and nutrition on crop establishment and yield of winter oilseed rape. *Aspect Appl. Biol.* **2014**, *125*, 21–30.
20. Talarczyk, W.; Łowinski, L. Tools and machines used in various tillage systems. *Tech. Rol. Ograd. I Leśna* **2017**, *2*, 11–14. (In Polish)
21. Jaskulska, I.; Jaskulski, D. Strip-till one-pass technology in central and eastern Europe: A Mzuri Pro-Til Hybrid machine case study. *Agronomy* **2020**, *10*, 925. [\[CrossRef\]](#)
22. Jankowski, K.J. Winter and spring oilseed rape. In *Crop Production*; Kotecki, A., Ed.; Wrocław University of Environmental and Life Sciences: Wrocław, Poland, 2020; pp. 305–383. Volume 3. (In Polish)
23. Lal, R.; Reicosky, D.C.; Hanson, J.D. Evolution of the plough over 10,000 years and the rationale for no-till farming. *Soil Tillage Res.* **2007**, *93*, 1–12. [\[CrossRef\]](#)
24. Guan, D.; Zhang, Y.; Mahdi, M.; Kaisi, A.; Wang, Q.; Zhang, M.; Li, Z. Tillage practices effect on root distribution and water use efficiency of winter wheat under rain-fed condition in the North China Plain. *Soil Tillage Res.* **2015**, *146*, 286–295. [\[CrossRef\]](#)
25. De Vita, P.; Di Paolo, E.; Fecondo, G.; Di Fonzo, N.; Pisante, M. No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture in southern Italy. *Soil Tillage Res.* **2007**, *92*, 69–78. [\[CrossRef\]](#)
26. Jabro, J.D.; Stevens, W.B.; Iverson, W.M.; Evans, R.G.; Allen, B.L. Crop water productivity of sugarbeet as affected by tillage. *Agron. J.* **2014**, *106*, 2280–2286. [\[CrossRef\]](#)
27. Myalo, V.V.; Demshuk, E.V.; Kuzmin, D.E.; Soyunov, A.S.; Sabiev, U.K. Relevance for using machines appropriate to strip tillage. *Mater. Sci. Eng.* **2019**, *582*, 012025. [\[CrossRef\]](#)
28. Tonev, T.; Mitkov, A. Chemical control of weeds in major field crops. *Farming Plus* **2015**, *2*, 33–44.
29. Deligios, P.A.; Carboni, G.; Farci, R.; Solinas, S.; Ledda, L. Low-input herbicide management: Effects on rapeseed production and profitability. *Sustainability* **2018**, *10*, 2258. [\[CrossRef\]](#)
30. Pacanoski, Z. Application time and herbicide rate effects on weeds in oilseed rape (*Brassica napus* var. *oleifera*). *Herbologia* **2014**, *14*, 33–45. [\[CrossRef\]](#)
31. Meier, U. *Growth Stages of Mono- and Dicotyledonous Plants: BBCH Monograph*; Julius Kühn-Institut: Quedlinburg, Germany, 2018; Available online: <https://www.julius-kuehn.de/media/Veroeffentlichungen/bbch%20epaper%20en/page.pdf> (accessed on 14 October 2023).
32. Hamzei, J.; Nasab, A.D.M.; Khoie, F.R.; Javanshir, A.; Moghaddam, M. Critical period of weed control in three winter oilseed rape (*Brassica napus* L.) cultivars. *Turk. J. Agric. For.* **2007**, *31*, 83–90.

33. Plaza, E.H.; Navarrete, L.; González-Andújar, J.L. Intensity of soil disturbance shapes response trait diversity of weed communities: The long-term effects of different tillage systems. *Agric. Ecosys. Environ.* **2015**, *207*, 101–108. [\[CrossRef\]](#)
34. Nichols, V.; Verhulst, N.; Cox, R.; Govaerts, B. Weed dynamics and conservation agriculture principles: A review. *Field Crops Res.* **2015**, *183*, 56–68. [\[CrossRef\]](#)
35. Małecka-Jankowiak, I.; Blecharczyk, A.; Sawinska, Z.; Piechota, T.; Waniorek, B. Impact of crop sequence and tillage system on weed infestation of winter wheat. *Fragm. Agronom.* **2015**, *32*, 54–63.
36. Bankina, B.; Balodis, O.; Gaile, Z. Advances of fungicide application for winter oilseed rape. In *Fungicide*; Carisse, O., Ed.; InTech: Rijeka, Croatia, 2010; pp. 157–176.
37. Balodis, O.; Gaile, Z. Fungicide as growth regulator application effect on winter oilseed rape (*Brassica napus* L.) autumn growth. *J. Agric. Sci.* **2011**, *22*, 7–12.
38. Zamani-Noor, N.; Knüfer, J. Effects of host plant resistance and fungicide application on phoma stem canker, growth parameters and yield of winter oilseed rape. *Crops Prot.* **2018**, *112*, 313–321. [\[CrossRef\]](#)
39. Kalniņš, E.; Gaile, Z. Winter oilseed rape yield formation depending on sowing time and application of plant growth regulator. In Proceedings of the 14th International Scientific Conference “Students on their way to science”, Jelgawa, Latvia, 26 April 2019.
40. Matysiak, K.; Kaczmarek, S. Effect of chlorocholine chloride and triazoles—tebuconazole and flusilazole on winter oilseed rape (*Brassica napus* var. *oleifera* L.) in response to the application term and sowing density. *J. Plant Prot. Res.* **2013**, *53*, 78–88. [\[CrossRef\]](#)
41. Kuai, J.; Yang, Y.; Sun, Y.; Zhou, G.; Zuo, Q.; Ling, X. Paclobutrazol increases canola seed yield by enhancing lodging and pod shatter resistance in *Brassica napus* L. *Field Crops Res.* **2015**, *180*, 10–20. [\[CrossRef\]](#)
42. Wenda-Piesik, A.; Hoppe, S. Evaluation of hybrid and population cultivars on standard and high-input technology in winter oilseed rape. *Acta Agric. Scan. Sect. B Soil Plant Sci.* **2018**, *68*, 678–689. [\[CrossRef\]](#)
43. Groth, D.A.; Sokółski, M.M.; Jankowski, K.J. A multi-criteria evaluation of the effectiveness of nitrogen and sulfur fertilization in different cultivars of winter rapeseed—Productivity, economic and energy balance. *Energies* **2020**, *13*, 4654. [\[CrossRef\]](#)
44. Jarecki, W. The reaction of winter oilseed rape to different foliar fertilization with macro- and micronutrients. *Agriculture* **2021**, *11*, 515. [\[CrossRef\]](#)
45. Sikorska, A.; Gugała, M.; Zarzecka, K. The response of different kinds of rapeseed cultivars to foliar application of nitrogen, sulphur and boron. *Sci. Rep.* **2021**, *11*, 21102. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Poisson, E.; Trouverie, J.; Brunel-Muguët, S.; Akmouche, Y.; Pontet, C.; Pinochet, X.; Avicé, J.C. Seed yield components and seed quality of oilseed rape are impacted by sulfur fertilization and its interactions with nitrogen fertilization. *Front. Plant Sci.* **2019**, *10*, 458. [\[CrossRef\]](#)
47. Öztürk, Ö. Effects of source and rate of nitrogen fertilizer on yield, yield components and quality of winter rapeseed (*Brassica napus* L.). *Chil. J. Agric. Res.* **2010**, *70*, 132–141. [\[CrossRef\]](#)
48. Litke, L.; Gaile, Z.; Ruža, A. Effect of nitrogen rate on nitrogen use efficiency in winter oilseed rape (*Brassica napus*). *Res. Rural Develop.* **2019**, *2*, 43–49. [\[CrossRef\]](#)
49. Jankowski, K.J.; Załuski, D.; Sokółski, M.M. Canola-quality white mustard: Agronomic management and seed yield. *Ind. Crops Prod.* **2020**, *145*, 112138. [\[CrossRef\]](#)
50. IUSS Working Group WRB. *World Reference Base for Soil Resources*, 2nd ed.; World Soil Resources Reports No. 103; FAO: Rome, Italy, 2022; p. 132.
51. Szatkowski, A.; Sokółski, M.; Załuski, D.; Jankowski, K.J. The effects of agronomic management in different tillage systems on the fall growth of winter oilseed rape. *Agriculture* **2023**, *13*, 440. [\[CrossRef\]](#)
52. Jankowski, K.J.; Sokółski, M.; Załuski, D. Winter oilseed rape: Agronomic management in different tillage systems and energy balance. *Energy* **2023**, *277*, 127590. [\[CrossRef\]](#)
53. STATSOFT INC. Statistica (Data Analysis Software System). 2017. Available online: <http://www.statsoft.com> (accessed on 28 October 2023).
54. Mitchell, J.P.; Singh, P.N.; Wallender, W.W.; Munk, D.S.; Wroble, J.F.; Horwath, W.R.; Hogan, P.; Robert, R.; Hanson, B.R. No-tillage and high-residue practices reduce soil water evaporation. *Calif. Agric.* **2012**, *66*, 55–61. [\[CrossRef\]](#)
55. Byrne, R.K.; McCabe, T.; Forristal, P.D. The impact of crop establishment systems in combination with applied nitrogen management on the establishment, growth and yield of winter oilseed rape in a mild Atlantic climate. *Eur. J. Agron.* **2022**, *139*, 126566. [\[CrossRef\]](#)
56. Franek, M. Reacting of six winter oilseed rape cultivars to herbicides applied post sowing and post emergence. *Rośliny Oleiste Oilseed Crops* **2001**, *22*, 91–96. (In Polish)
57. Miliuviene, L.; Novickiene, L.; Gaveliene, V.; Brazauskiene, I.; Pakalniskyte, L. Possibilities to use growth regulators in winter oilseed rape growing technology. The effect of retardant analogues on oilseed rape growth. *Agron. Res.* **2004**, *2*, 207–215.
58. Ijaz, M.; Mahmood, K.; Honermeier, B. Interactive role of fungicides and plant growth regulator (Trinexapac) on seed yield and oil quality of winter rapeseed. *Agronomy* **2015**, *5*, 435–446. [\[CrossRef\]](#)
59. Jankowski, K.J. Habitat, Agrotechnological and Economic Conditions of Winter Rapeseed Production for Consumption and Energy Purposes. Habilitation Thesis, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland, 2007; pp. 1–174. (In Polish).
60. Matysiak, K.; Kaczmarek, S.; Adamczewski, K. The influence of trinexapac-ethyl, chlorocholine chloride, metconazole and tebuconazole on plant morphology and yield of winter oilseed rape depending on time of application. *Rośliny Oleiste Oilseed Crops* **2010**, *31*, 361–372. (In Polish)

61. Ijaz, M.; Honermeier, B. Effect of different fungicides on seed yield and grain quality of rapeseed under two levels of nitrogen fertilization. In Proceedings of the 13th International Rapeseed Congress, Prague, Czechia, 5–8 June 2011; pp. 11–15.
62. Ijaz, M.; Honermeier, B. Effect of triazole and strobilurin fungicides on seed yield formation and grain quality of winter rapeseed (*Brassica napus* L.). *Field Crops Res.* **2012**, *130*, 80–86. [[CrossRef](#)]
63. Butkutė, B.; Šidlauskas, G.; Brazauskienė, I. Seed yield and quality of winter oilseed rape as affected by nitrogen rates, sowing time, and fungicide application. *Commun. Soil Sci. Plant Anal.* **2006**, *37*, 2725–2744. [[CrossRef](#)]
64. White, C.A.; Roques, S.E.; Berry, P.M. Effects of foliar-applied nitrogen fertilizer on oilseed rape. *J. Agric. Sci.* **2015**, *153*, 42–55. [[CrossRef](#)]
65. Varényiová, M.; Ducsay, L. Effect of increasing spring doses of nitrogen on yield and oil content in seeds of oilseed rape (*Brassica napus* L.). *Acta Fyto. Zoot.* **2016**, *19*, 29–34. [[CrossRef](#)]
66. Wielebski, F.; Wójtowicz, M.; Liersch, A. Response of new forms of winter oilseed rape with modified fatty acid composition to nitrogen and sulfur fertilization. *J. Plant Nutr.* **2022**, *45*, 2360–2379. [[CrossRef](#)]
67. Fazili, I.S.; Masoodi, M.; Ahmad, S.; Jamal, A.; Khan, J.S.; Abdin, M.Z. Interactive effect of sulfur and nitrogen on growth and yield attributes of oilseed crops (*Brassica campestris* L. and *Eruca sativa* Mill.) differing in yield potential. *J. Plant Nutri.* **2010**, *33*, 1216–1228. [[CrossRef](#)]
68. Santos, R.F.; Borsoi, A.; Secco, D.; de Souza, S.N.M.; Frigo, E.P. Nitrogen and sulfur sources in the culture of *Brassica napus* L. var. oleifera. *J. Food Agric. Environ.* **2012**, *10*, 516–518.
69. Kozłowska-Strawska, J. Fat content and fatty acid composition in oilseed rape grown in the Lubelski Region under different levels of soil sulphur fertility. *Ecol. Chem. Eng.* **2012**, *19*, 191–201. [[CrossRef](#)]
70. Barczak, B.; Barczak, T.; Skinder, Z.; Piotrowski, R. Proportions of nitrogen and sulphur in spring rapeseeds depending on fertilization with these elements. *J. Elementol.* **2020**, *25*, 1385–1398. [[CrossRef](#)]
71. Sienkiewicz-Cholewa, U.; Kieloch, R. Effect of sulphur and micronutrients fertilization on yield and fat content in winter rape seeds (*Brassica napus* L.). *Plant Soil Environ.* **2015**, *161*, 64–170. [[CrossRef](#)]
72. Pużyńska, K.; Kulig, B.; Halecki, W.; Lepiarczyk, L.; Pużyński, S. Response of oilseed rape leaves to sulfur and boron foliar application. *Acta Physiol. Plant.* **2018**, *40*, 169. [[CrossRef](#)]

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