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A Multi-Criteria Evaluation of the Effectiveness of Nitrogen and Sulfur Fertilization in Different Cultivars of Winter Rapeseed—Productivity, Economic and Energy Balance

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Abstract: This article presents the results of a three-year experiment involving a multi-criteria evaluation (productivity, economic and energy balance) of the effectiveness of nitrogen (N) and sulfur (S) fertilization in different cultivars of winter oilseed rape (open-pollinated, semi-dwarf hybrid, long-stem hybrid) grown in north-eastern (NE) Poland. The yield of the semi-dwarf cultivar was 11% lower than the yield of the long-stem hybrid cultivar and 18% higher than the yield of the open-pollinated cultivar. In all cultivars, N fertilization improved yields up to a rate of 180 kg ha^{-1} and up to a rate of 230 kg ha^{-1} in years with low precipitation in spring and summer. Seed yield increased in all cultivars in response to S fertilization at 40 kg ha^{-1}. Higher rates of N fertilizer decreased the content of crude fat and glucosinolates (GLS) and increased the concentration of total protein in all cultivars. Sulfur fertilization increased the content of total protein (in long-stem cultivars) and GLS (in all cultivars). Production costs ranged from €542–624 ha^{-1} (≤130 kg N ha^{-1}) to €619–697 ha^{-1} (≥180 kg N ha^{-1}). The demand for energy in the production of winter rapeseed ranged from 14.5–19.3 GJ ha^{-1} (≤130 kg N ha^{-1}) to 22.4–27.0 GJ ha^{-1} (≥180 kg N ha^{-1}).

Keywords: *Brassica napus* L.; cultivar; fertilization; biomass yield and quality; profitability; energy balance

1. Introduction

The global production of oilseed crops is estimated at 550 million Mg yr^{-1}. The leading oilseed crops in the world are soybeans (*Glycine hispida* (Moench) Maxim.) (63%), rapeseed (*Brassica napus* (L.) *ssp. oleifera* (Metzg)) (12%) and sunflower (*Helianthus annuus* L.) (9%) [1]. Rapeseed became a major oilseed crop mainly due to biological progress [2]. The discovery of genetic sources of variability in the main seed quality traits, that is, the content of erucic acid (EA) and glucosinolates (GLS), were the milestones that contributed to advances in rapeseed production and an increase in the area under rapeseed. The first EA-free variety was derived from the forage spring rapeseed cultivar Liho in 1961 [3]. In the late 1950s, Dr. Krzymański discovered that spring rapeseed cv. Bronowski contained ten-times less GLS than the remaining varieties of *B. napus* [4]. Owing to these breakthrough discoveries, contemporary rapeseed cultivars grown for the food and feed processing industries contain practically no EA in oil and are characterized by low levels of GLS in fat-free seed residues. These rapeseed lines are referred to as double-low, double-zero or canola-quality cultivars [5]. The production and commercialization of canola-quality rapeseed has led to a rapid increase in the demand for these cultivars in the food and feed processing industries [6]. In the last 15 years (2003–2017), the area under rapeseed and global rapeseed production continued to increase at a rate of 0.75 million ha yr^{-1} and 2.69 million Mg yr^{-1}, respectively [1]. The European Union, Canada, China and India are the leading rapeseed producers. French and German farmers supply 24% and 20% of the rapeseed produced annually in the European Union (5.20 million Mg and 4.28 million Mg, respectively) [1].

The production of rapeseed was further intensified by the discovery and development of systems for controlling cross-pollination to utilize the heterosis effect [7]. The yields of hybrid winter oilseed rape cultivars grown in Europe exceed those of open-pollinated cultivars by around 7–17% [8,9]. The heterosis effect is also observed in seed quality traits [9] and plant responses to agronomic [10] and climatic factors [8].

At present, the main goals of oilseed rape breeding are to—(i) increase yields, mainly in hybrid cultivars [11]; (ii) improve agronomic traits, mainly resistance to pre-harvest seed shattering [12], drought [13], high/low temperature [14,15], soil salinity [16] and lodging [17]; (iii) increase resistance to disease and pests [18,19]; (iv) decrease the content of biologically active compounds that compromise the feed value of non-fat seed residues [20]. The introduction of winter oilseed rape cultivars with a determinate growth habit was important from a commercial perspective [10]. The yields of semi-dwarf cultivars are 1–7% to even 18% lower relative to long-stem cultivars [9,10,21,22]. The yields of semi-dwarf and long-stem cultivars are comparable under N-deficient conditions [23]. Semi-dwarf hybrids are more resistant to lodging and are easier to harvest, which increases their energy efficiency [23]. They are also recommended for cool climate regions due to their higher winter hardiness [24].

In Europe, rapeseed yields range from 1.6–1.9 Mg ha^{-1} (Spain, Finland, Greece) to 4.1–4.3 Mg ha^{-1} (Netherlands, Ireland, Denmark, Belgium) [1]. In the last 15 years, rapeseed yields in the EU continued to increase at 10–30 kg ha^{-1} yr^{-1} (Finland, Greece, Luxembourg, Spain) to 130–140 kg ha^{-1} yr^{-1} (Bulgaria, Hungary, Lithuania, Romania) [1]. The observed increase in yields can be attributed not only to the cultivation of high-yielding cultivars but also to higher agricultural inputs [10]. Despite significant technological progress in agriculture, nitrogen (N) fertilization is still the key factor in rapeseed cultivation [8]. The N demand of winter oilseed rape ranges from 5.5 kg N 100 kg^{-1} to 6.1 kg N 100 kg^{-1} seeds [8,25]. However, the high N demand of winter oilseed rape is accompanied by relatively low nitrogen use efficiency (NUE) [26–28]. The NUE of winter oilseed rape has been estimated at 10 kg dry matter (DM) seeds kg^{-1} N and it is considerably lower in comparison with spring malting barley (21 kg DM seeds kg^{-1} N), winter wheat grown for forage (25 kg DM seeds kg^{-1} N) and sugar beets (69 kg DM seeds kg^{-1} N) [29]. The optimal N rate for rapeseed production is difficult to establish because the yield-forming effects of N are considerably influenced by agroecological conditions, crop rotation, agricultural inputs, form of N fertilizer, fertilization technology [8] and genotype [30].

The growth and development of *Brassica* crops is also affected by sulfur (S) which is found in structural compounds (amino acids, proteins, enzymes) and plays important metabolic functions in plants (protein, carbohydrate, fat and chlorophyll synthesis, photosynthesis) [31]. The demand for S is determined mainly by crop species and yield. Plants of the families *Brassicaceae* and *Liliaceae* have the highest S requirements (40–80 kg ha^{-1}). The demand for S is moderate in legumes (30–40 kg ha^{-1}) and lowest (15–25 kg ha^{-1}) in cereals [32]. The availability of S in soil is affected by a combination of factors such as S deposition in soil, mineralization of organic forms and the amount and distribution of precipitation [33]. Lower SO_2 emissions and higher proportions of S-loving plants in agricultural ecosystems necessitate S fertilization, in particular in high-input production systems [34]. Sulfur deficit poses a serious problem in modern agriculture and it significantly compromises crop production not only in Europe but also in many regions of Australia, New Zealand, USA, Canada, Latin America and Asia [35]. In S-deficient soils, S fertilization increases rapeseed yields by up to 65–74% [36,37]. In soils moderately abundant in this nutrient, S fertilization increases yields by only several percent [34,38].

Sulfur fertilization not only exerts direct effects on the seed yield of crops in the family *Brassicaceae* but also indirectly improves the agronomic effectiveness of N fertilizers [39–42]. In a study by McGrath and Zhao [43], N rates exceeding 180 kg ha^{-1} increased rapeseed yields by 42–267% (0.7–1.6 Mg ha^{-1})

only in combination with a soil-applied S rate of 40 kg S ha^{-1}. Similar results were reported by Ma et al. [42], Jankowski [44], Ahmad et al. [45], Lucas et al. [46] and Filipek-Mazur et al. [47] in open-pollinated and hybrid oilseed rape cultivars. The combined application of N and S produced similar effects in other *Brassica* crops, including camelina (*Camelina sativa* (L.) Crantz) [48–50], brown mustard (*Brassica juncea* (L.) Czern.) [51,52], white mustard (*Sinapis alba* L.) [53,54] and turnip rape (*Brassica campestris* L.) [41,51].

The processing suitability of rapeseed is influenced by the content of total protein and crude fat. The seeds of winter oilseed rape contain 406–490 g kg^{-1} DM of crude fat [34,55–57] and 190–260 g kg^{-1} DM of total protein [34,57]. Oilseed crops of the families *Brassicaceae* and *Liliaceae* are also capable of synthesizing GLS [58]. The GLS content of canola-quality winter rapeseed from the Polish National List of Agricultural Plant Varieties ranges from 9.1 μM g^{-1} to 14.7 μM g^{-1} seeds [59] Protein and non-protein amino acids, mostly methionine (alkenyl GLS), tryptophan (indole GLS), phenylalanine and thyrosine (aromatic GLS), are the direct precursors of GLS [60]. Double-low cultivars of oilseed rape contain mostly progoitrin, gluconapin (alkenyl GLS) and 4-hydroxyglucobrassicin (indole GLS), accounting for 90% to 91% of total GLS [34].

The crude fat content of rapeseed and other *Brassica* crops is negatively correlated with total protein concentration. In turn, total protein is positively correlated with N fertilizer rates [48,50,53,54,61–64]. Therefore, the N-induced increase in total protein content [65,66] can decrease the crude fat content of rapeseed [8,61,65–67]. A similar correlation was noted in alternative *Brassica* crops, including camelina [48,50,63], brown mustard [68] and white mustard [53,54]. Late application of N fertilizers intensifies the decrease in crude fat concentration [66]. Nitrogen fertilization and the crude fat content of rapeseed are not bound by a negative correlation only when N does not exert a yield-forming effect [69]. Nitrogen also affects the biosynthesis of different GLS fractions [61,70–73]. High supply of N generally decreases the biosynthesis of alkenyl GLS and increases the biosynthesis of indole GLS in rapeseed [74].

Sulfur fertilization exerts a yield-forming effect on crops of the family *Brassicaceae* and it can also considerably influence the quality of oil, fat-free seed residues and harvest residues [34,49,54,75–78]. Sulfur exerts varied effects on the crude fat content of rapeseed. Sulfur fertilization decreased the crude fat content of rapeseed in the studies conducted by Fismes et al. [55] and Egesel et al. [56]. According to Filipek-Mazur et al. [47], Ijaz and Honermeier [57] and Jankowski et al. [34], S had no significant influence on crude fat concentration in rapeseed. An S-induced increase in the crude fat content of winter and spring cultivars of oilseed rape was observed by Szulc et al. [79], Ahmad et al. [80], Bahmanyar and Poshtmasari [81] and Sienkiewicz-Cholewa and Kieloch [82]. In a study by Jankowski et al. [83], the influence of S fertilization on the crude fat content of oilseed rape varied depending on weather conditions. Sulfur decreased crude fat content in years with relatively high precipitation during ripening. In growing seasons with average precipitation, S fertilization had no significant influence on crude fat content. Sulfur not only affects the accumulation of crude fat in seeds but it also modifies the fatty acid (FA) profile. The availability of S during seed development inhibits the conversion of oleic acid to EA, thus improving the quality of rapeseed oil [84]. The important role played by S in plants results also from its presence in sulfur-containing amino acids (cystine, cysteine and methionine) [85]. In plants, more than 90% of S is accumulated in the form of sulfur-containing amino acids [86]. Sulfur deficiency generally decreases the content and quality of total protein in the seeds of winter oilseed rape by reducing the concentrations of nutritionally important essential amino acids [56,75,87]. However, the correlation between S fertilization and the total protein content of *Brassica* crops is generally weak and it varies across years [34,38,50,84,88–91]. Sulfur fertilization plays a key role in the biosynthesis of GLS [34,38,58,75,92–94], mainly alkenyl GLS [34]. Long-term experiments conducted by Wielebski [95] and Wielebski [96] revealed a significant increase in the GLS content of all double-low cultivars of winter rapeseed (open-pollinated, composite and restored hybrids, double haploid). The GLS content of rapeseed increases significantly in response to high S fertilization rates, in particular in S-deficient soils [97].

Oilseed rape, in particular winter cultivars, requires intensive farming and its yields are strongly determined by agricultural inputs [98,99]. Production costs, yields and, consequently, the economic performance of rapeseed are determined by the prices of seeds and agricultural inputs [100–102] as well as the applied production technology [103]. High-input technologies are characterized by higher input costs but also higher productivity. In Europe, rapeseed production costs in high-input technologies range from €500 ha^{-1} to even €1000 ha^{-1}. Production costs are around 12% lower in integrated technologies [104] and up to 40% lower in low-input technologies [105]. The economic performance of winter oilseed rape is also largely determined by genetic factors (cultivar) because the yields of various cultivars can differ by 0.7–1.1 Mg ha^{-1} [21,106] to 1.8 Mg ha^{-1} [9].

The production of agricultural biomass is a strategic sector from the perspective of global food security, which remains to be the main but no longer the only priority in agricultural production. Biomaterials are also being converted to bioproducts and bioenergy to counteract the threats to global energy security [107–115]. Environmental problems and the rising cost of fossil fuels have increased the significance of research into the energy efficiency of agricultural crops. Efforts are being made to improve the energy balance of biomass [116]. Energy consumption in agriculture is directly linked with technological progress. High-input production technologies have increased the availability of food but have also made the agricultural sector more dependent on fossil fuels [117]. Rapeseed production in high-input systems entails higher energy consumption and lower energy efficiency but higher energy output per unit area [108]. Therefore, production systems characterized by different levels of agricultural inputs should be evaluated not only in terms of agricultural productivity (yield and yield quality) and economic performance but also in terms of energy efficiency [108]. A multi-criteria approach can be applied to evaluate the effectiveness of various technologies in the production of new crop cultivars.

The objective of this study was to identify N and S fertilization systems characterized by the highest agricultural productivity, economic performance and energy efficiency in the production of various cultivars of winter oilseed rape (open-pollinated, long-stem hybrid and semi-dwarf hybrid) in north-eastern (NE) Poland. The effect of nitrogen and sulfur fertilization on the biomass yield, harvest index, nitrogen use efficiency, marginal nitrogen use efficiency, seed quality (crude fat content, total protein content, fatty acid composition, lower heating value, qualitative and quantitative composition, GLS content), production value, revenue per hectare, profitability index, energy inputs, energy output, energy gain and the energy efficiency ratio of various winter oilseed rape cultivars was also evaluated.

2. Materials and Methods

2.1. Field Experiment

The experiment was conducted in 2011–2014 at the Agricultural Experiment Station in Bałcyny (53°42′ N, 19°51′ E; NE Poland) owned by the University of Warmia and Mazury in Olsztyn. The experimental factors were as follows—(i) winter rapeseed cultivar: long-stem open-pollinated (cv. Adriana); long-stem hybrid (cv. Artoga); and semi-dwarf hybrid (cv. PR44 D06); (ii) N fertilizer rate (kg ha^{-1}): 80, 130, 180 and 230; (iii) S fertilizer rate (kg ha^{-1}): 0, 40 and 80. A single N dose of up to 130 kg ha^{-1} was applied in BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) stage 33–35 [118] as ammonium nitrate (34% N) or ammonium sulfate (24% S and 21% N). Higher N rates (180 and 230 kg ha^{-1}) were split into two doses: 130 kg N ha^{-1} in BBCH stage 33–35 and 50 or 100 kg N ha^{-1} in BBCH stage 50–52. The second N dose was applied as ammonium nitrate (34% N). Sulfur was applied with the first N dose (BBCH 33–35), in the form of ammonium sulfate (24% S and 21% N).

The experiment had a split-split plot design with three replications. Plot size was 15 m^2 (10 m by 1.5 m). Spring barley (*Hordeum vulgare* L.) was the preceding crop in all years of the experiment. The following tillage operations were carried out—skimming, pre-sowing plowing and soil loosening before sowing. The following fertilizers were applied before sowing—30 kg N ha^{-1} (ammonium nitrate, 34% N), 80 kg P_2O_5 ha^{-1} (enriched superphosphate, 40% P_2O_5) and 120 kg K_2O ha^{-1} (potash salt, 60% K_2O). Dressed seeds (fludioxonil, metaxyl-M, thiamethoxam) of winter oilseed rape cultivars were sown in mid (years 2 and 3) or late August (year 1) with a plot seeder at 60 (hybrid cultivars) or 80 (open-pollinated cultivar) of germinating seeds per 1 m^2, at a depth of 2.0–2.5 cm. Metazachlor (832.5 g ha^{-1}) and quinmerac (207.5 g ha^{-1}) were used to control weed infestation immediately after sowing. Insecticides were applied four times during the spring growing season—(i) 288 g ha^{-1} chlorpyrifos and 30 g ha^{-1} cypermethrin (BBCH 33); (ii) 60 g ha^{-1} thiacloprid and 6 g ha^{-1} deltamethrin (BBCH 52); (iii) 12 g alpha-cypermethrin (BBCH 63); (iv) 2.4 g ha^{-1} acetamiprid (BBCH 66). Rapeseed was harvested on 7–10 July, in the stage of 89 BBCH, with a small-plot harvester.

Each year, the experiment was established on Haplic Luvisol (LV-ha) developed from boulder clay [119]. In order to determine the chemical properties of soil, composite samples consisting of 8 to 10 cores were collected annually (before fertilization and sowing) from each plot to a depth of 0–20 cm (Table 1).

Table 1. Chemical properties of soil.

Years	pH	C_{org} (g kg^{-1})	Available Macronutrients (mg kg^{-1})			
			P	K	Mg	SO_4^{2-}
2011/2012	5.9	9.0	21.3	59.3	52.0	9.2
2012/2013	5.7	8.9	20.4	57.9	49.0	7.8
2013/2014	6.3	9.9	26.2	82.7	68.0	12.5

Chemical analyses of soil were performed according to the methods described by Sokólski et al. [120].

2.2. Plant Materials

The biomass yield of winter rapeseed (seeds and straw) from each plot was determined by weight after threshing and it was expressed in DM per hectare, taking into account the moisture content of the samples after oven-drying at 105 °C (FD 53 Binder GmbH, Tuttlingen, Germany). The harvest index (HI) was calculated with the following formula (Equation (1)):

$$HI = \frac{\text{Seed yield (Mg DM ha}^{-1})}{\text{Seed and straw yield (Mg DM ha}^{-1})}. \quad (1)$$

The below formula was used to calculate nitrogen use efficiency (NUE) (Equation (2)) [8]:

$$NUE = \frac{\text{Seed yield (kg DM ha}^{-1})}{\text{N rate (kg ha}^{-1})}. \quad (2)$$

Marginal nitrogen use efficiency was calculated with the below formula (Equation (3)) [121]

$$MNUE = \frac{\Delta Y}{\Delta R_N}, \quad (3)$$

where:
MNUE—Marginal nitrogen use efficiency (kg seeds per 1 kg N)
ΔY—increase in seed yield (kg) for the applied nitrogen rates
ΔR_N—increase in nitrogen rate (kg).

2.3. Seed Quality Analysis

The procedure for determining the concentrations of crude fat, total protein and GLS in winter oilseed rape seeds and the FA profile of oil was described previously by Jankowski et al. [122].

2.4. Economic Analysis

The analysis of rapeseed production costs included the costs associated with labor, seeds, fertilizers, crop protection, the operation of tractors and farming machines and fuel. The costs of input materials and the operation of tractors and agricultural machines were estimated based on actual consumption, market prices (4Q 2019) and the technical parameters of agricultural machines (measured by the authors, Table 2) and labor (€4.60 h^{-1}). The economic efficiency of winter oilseed rape production was determined based on the following indicators—production value, revenue per hectare and the profitability index [120].

2.5. Energy Analysis

The relevant data were obtained based on direct measurements of diesel oil consumption, labor and the field capacity of farming machines and equipment in the Agricultural Experiment Station in Bałcyny for standard agricultural operations in large-area farms (Table 2). The energy equivalents of the agricultural inputs were determined based on literature data [123–125].

The lower heating value (LHV), energy value of seeds (energy output), energy gain and the energy efficiency ratio were calculated based on the methods described by Sokólski et al. [120].

2.6. Statistical Analysis

The data relating to seed and straw yield, nitrogen use efficiency, harvest index and seed quality traits were processed by split-split-plot mixed model variance, where cultivar, N and S fertilization were the fixed effects and experimental years and replications nested within years were the random effects. Post-hoc multiple comparisons were performed using Tukey's test (HSD). The results were considered statistically significant at $\alpha = 0.05$. All analyses were conducted with the use of Statistica ver. 13.3 software (Tibco Software Inc., Palo Alto, USA) [126]. The *F*-values of ANOVA are presented in Table 3.

Table 2. Technical parameters of agricultural machines, machine performance and fuel consumption during winter oilseed rape production.

Farming Operations	Engine Power of Self-Propelled Machine (kW) [a]	Parameters of Accompanying Machine	Service Life (h)		Weight (kg)		Performance of Self-Propelled Machine and Accompanying Machine (ha h^{-1}) [f]	Fuel Consumption (l h^{-1}) [f]
			Self-Propelled Machine	Accompanying Machine	Self-Propelled Machine	Accompanying Machine		
Tillage (5–8 cm)	130	4.25 [b]	10,000	1500	7105	5100	3.0	18.0
Pre-sowing plowing (18–20 cm)	130	5 [c]	10,000	1400	7105	2370	1.8	26.0
Sowing	184	4.0 [b]	10,000	1800	10,980	5600	3.5	29.5
Mineral fertilization	130	24.0 [b]	10,000	2000	7105	685	13.5	8.7
Chemical crop protection	94	24.0 [b]	10,000	3000	5166	5600	10.0	7.6
Seed harvest	370	10.5 [b]	2800	-	20,000	-	2.8-3.5 [g]	45.0–50.0 [g]
Seed transport	130	10 [d]	10,000	1400	7105	2600	-	8.0
Loading	55	2500 [e]	10,000	-	4920	-	-	4.0

[a] tractor/harvester/loader; [b] working width (m); [c] number of furrows; [d] carrying capacity (Mg); [e] load capacity (kg); [f] average of 3 years; [g] differences resulting from variations in yield.

Table 3. *F*-test statistics in ANOVA.

Trait	Y	Cv.	N	S	Y × Cv.	Y × N	Y × S	Cv. × N	Cv. × S	N × S	Y × Cv. × N	Y × Cv. × S	Y × N × S	Cv. × N × S	Y × Cv. × N × S
Seed yield (Mg ha^{-1} DM)	2.49 *ns*	226.67 **	122.90 **	5.47 *	122.96 **	8.50 **	0.46 *ns*	1.39 *ns*	1.63 *ns*	0.75 *ns*	1.32 *ns*	1.72 *ns*	0.41 *ns*	0.49 *ns*	0.39 *ns*
NUE (kg seed per 1 kg N)	1.57 *ns*	171.31 **	1629.93 **	2.97 *ns*	89.01 **	1.90 *ns*	0.40 *ns*	12.99 **	0.89 *ns*	0.26 *ns*	0.44 *ns*	0.16 *ns*	0.28 *ns*	0.29 *ns*	0.51 *ns*
Straw yield (Mg ha^{-1} DM)	111.44 **	73.57 **	16.65 **	0.08 *ns*	7.80 **	3.71 *	1.49 *ns*	0.83 *ns*	0.17 *ns*	0.17 *ns*	1.45 *ns*	0.71 *ns*	0.75 *ns*	0.78 *ns*	0.56 *ns*
Harvest index	142.64 **	44.62 **	22.62 **	2.99 *ns*	1.28 *ns*	2.82 *	1.05 *ns*	2.20 *	0.41 *ns*	0.82 *ns*	1.26 *ns*	0.59 *ns*	1.18 *ns*	1.44 *ns*	0.82 *ns*
Crude fat content (g kg^{-1} DM)	75.93 **	27.97 **	33.62 **	1.35 *ns*	1.72 *ns*	3.16 **	0.43 *ns*	3.87 **	0.86 *ns*	1.38 *ns*	1.67 *ns*	0.53 *ns*	0.09 *ns*	1.32 *ns*	0.27 *ns*
$C_{18:1}$ (%)	3.73 *	199.78 **	5.69 **	0.60 *ns*	0.03 *ns*	0.02 *ns*	0.05 *ns*	1.31 *ns*	1.18 *ns*	1.69 *ns*	0.04 *ns*	0.02 *ns*	0.01 *ns*	1.36 *ns*	0.07 *ns*
$C_{18:2}$ (%)	3.41 *	244.11 **	5.20 **	0.11 *ns*	0.04 *ns*	0.01 *ns*	0.01 *ns*	0.97 *ns*	1.07 *ns*	1.12 *ns*	0.01 *ns*	0.01 *ns*	0.03 *ns*	1.71 *ns*	0.01 *ns*
$C_{18:3}$ (%)	2.68 *ns*	66.66 **	2.95 *	1.72 *ns*	0.07 *ns*	0.04 *ns*	0.23 *ns*	0.61 *ns*	2.24 *ns*	1.33 *ns*	0.10 *ns*	0.07 *ns*	0.05 *ns*	0.38 *ns*	0.20 *ns*
Total protein content (g kg^{-1} DM)	18.85 **	15.43 **	21.86 **	1.07 *ns*	0.33 *ns*	1.15 *ns*	0.06 *ns*	3.14 **	3.18 **	0.77 *ns*	0.84 *ns*	0.57 *ns*	0.61 *ns*	1.63 *ns*	0.47 *ns*
Total GLS content (μM g^{-1} DM)	16.26 **	720.66 **	17.32 **	378.79 **	0.02 *ns*	0.03 *ns*	0.01 *ns*	8.73 **	24.28 **	7.94 **	0.02 *ns*	0.02 *ns*	0.07 *ns*	1.47 *ns*	0.04 *ns*
Alkenyl GLS content (μM g^{-1} DM)	12.77 **	2875.77 **	34.48 **	1036.14 **	0.03 *ns*	0.05 *ns*	0.02 *ns*	17.53 **	71.52 **	20.73 **	0.03 *ns*	0.03 *ns*	0.12 *ns*	0.91 *ns*	0.06 *ns*
LHV (MJ kg^{-1})	26.48 **	7.63 **	0.14 *ns*	1.31 *ns*	2.14 *ns*	1.61 *ns*	1.23 *ns*	0.33 *ns*	0.67 *ns*	0.51 *ns*	0.98 *ns*	1.12 *ns*	0.96 *ns*	1.41 *ns*	1.35 *ns*

* significant $p < 0.05$; ** significant $p < 0.01$; *ns*—not significant; Y—growing season; Cv.—cultivar; N—nitrogen fertilization; S—sulfur fertilization; $C_{18:1}$—oleic acid; $C_{18:2}$—linoleic acid; $C_{18:3}$—linolenic acid; GLS—glucosinolate.

3. Results

3.1. Weather Conditions

The mean daily temperature during the autumn growing season (August–November) was somewhat higher than the long-term average (1981–2015) during the experiment (Table 4).

Table 4. Weather conditions during the experiment (2011–2014) vs. the long-term average (1981–2015) in the Agricultural Experiment Station in Bałcyny, Poland (53°35′46.4″ N, 19°51′19.5″ E). Adapted from [114].

Month	Year				1981–2015
	2011	2012	2013	2014	
Total Monthly Rainfall (mm)					
January	30	88	35	44	32
February	21	25	21	11	22
March	9	21	14	56	30
April	34	45	23	26	30
May	42	43	46	35	59
June	56	107	45	72	72
July	172	112	164	20	85
August	84	26	25	59	66
September	39	41	69	31	55
October	30	58	15	21	48
November	10	49	23	21	45
December	46	15	34	57	43
$\sum$	570	628	515	454	588
Mean Daily Temperature (°C)					
January	−1.5	−1.9	−4.4	−3.3	−2.4
February	−6.6	−7.2	−0.8	2.0	−1.8
March	2.0	3.4	−4.0	5.4	1.9
April	9.7	8.4	6.3	9.5	7.8
May	13.5	13.8	15.0	13.1	13.3
June	17.5	15.2	17.4	14.8	15.9
July	18.0	19.0	17.9	21.0	18.3
August	18.0	17.9	18.1	18.0	17.9
September	14.6	14.0	11.5	14.5	13.1
October	8.7	8.0	9.3	9.6	8.2
November	3.1	4.9	4.9	4.4	3.0
December	2.4	−3.4	2.3	−0.5	−0.7
$\bar{x}$	8.3	7.7	7.8	9.0	7.9

Total precipitation during the autumn growing season approximated the long-term average. Mild winters in the first and third year of the study (2011/2012 and 2013/2014) contributed to overwintering success. Below-zero temperatures (−1.9 °C to −7.2 °C) were noted only in January and February (year 1) or only in January (year 3). In the second year of the experiment (2012/2013), below−zero temperatures were observed during the entire winter dormancy period, that is, in December (−3.4 °C), January (−4.4 °C), February (−0.8 °C) and March (−4.0 °C). The amount and distribution of precipitation was most favorable for the spring and summer growth of winter oilseed rape in year 1 (2012). In the first year of the study, precipitation was determined at 307 mm between April and July and it was 25% higher than the long-term average. Precipitation exceeded the long-term average by 32–50% in April (45 mm), June (107 mm) and July (112 mm) of 2012. In the second year of the experiment (2013), spring precipitation exceeded the long-term average by 13% but its distribution was less favorable. Most rainfall (approx. 59%) occurred only during ripening (July), whereas precipitation in the preceding months (April–June) was below the long-term average (by 22–38%). In the third year of the study

(2014), total precipitation during the spring growing season amounted to only 153 mm and it was equivalent to 62% of the long-term average. Rainfall levels approximating the long-term average were noted only in June. The average daily temperature in spring and summer was similar to (years 1 and 2) or somewhat higher (year 3) than the long-term average (Table 4).

3.2. Biomass Yield and the Harvest Index

The yields of winter oilseed rape were stable and relatively high during the experiment (6.22−6.36 Mg ha^{-1}). The seed yield of the semi−dwarf cultivar (PR44 D06) was higher (by 0.48 Mg ha^{-1}) than the seed yield of the open−pollinated cultivar (Adriana) and lower (by 0.79 Mg ha^{-1}) than the seed yield of the long−stem hybrid cultivar (Artoga) (Table 5). The yield of the long−stem hybrid cultivar was particularly high (7.96 Mg ha^{-1}) in the first year of the study, when rainfall was abundant and evenly distributed during the spring and summer growing seasons (Figure 1). In all studied cultivars, N fertilizer rate of up to 180 kg ha^{-1} exerted a yield−forming effect (Table 5). The yield−forming effect of higher N rates (up to 230 kg ha^{-1}) was observed only in years with lower precipitation in the growing season (years 2 and 3) (Figure 2). The application of S at 40 kg ha^{-1} led to a small (3%) but significant increase in seed yield in all analyzed cultivars (Table 5). The genetic factor (cultivar) did not affect the effectiveness of S fertilizer. No significant interaction of N × S fertilization was found for this factor (Table 3).

Table 5. Productivity of winter oilseed rape biomass.

Parameter	Seed Yield (Mg ha^{-1} DM)	NUE (kg Seeds per 1 kg N)	Straw Yield (Mg ha^{-1} DM)	Harvest Index
		Growing Season		
2011/2013	6.36	45.68	10.91 ^{b}	0.333 ^{b}
2012/2013	6.27	46.35	9.71 ^{c}	0.362 ^{a}
2013/2014	6.22	45.44	11.86 ^{a}	0.313 ^{c}
		Cultivar		
Adriana	5.70 ^{c}	41.20 ^{c}	10.54 ^{b}	0.321 ^{c}
Artoga	6.97 ^{a}	50.95 ^{a}	11.80 ^{a}	0.339 ^{b}
PRD06	6.18 ^{b}	45.32 ^{b}	10.12 ^{c}	0.347 ^{a}
		Nitrogen Rate (kg ha^{-1}), across Years		
80	5.55 ^{c}	69.42 ^{a}	10.11 ^{b}	0.324 ^{b}
130	6.20 ^{b}	47.66 ^{b}	10.99 ^{a}	0.330 ^{b}
180	6.63 ^{a}	36.82 ^{c}	11.00 ^{a}	0.346 ^{a}
230	6.76 ^{a}	29.39 ^{d}	11.18 ^{a}	0.346 ^{a}
		Sulfur Rate (kg ha^{-1}), across Years		
0	6.21 ^{b}	45.45	10.85	0.333
40	6.40 ^{a}	46.57	10.83	0.340
80	6.25 ^{b}	45.46	10.79	0.337

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of letters denotes the non-significance of main effects.

Nitrogen use efficiency was 10–24% higher in long-stem (Artoga) and semi-dwarf (PR D06) hybrid cultivars than in the open-pollinated cultivar (Adriana) and 12% higher in the long-stem hybrid cultivar than in the semi-dwarf hybrid cultivar (Table 5). In the long-stem hybrid cultivar, NUE was particularly high in the first year of the study, characterized by above-average precipitation in the spring and summer growing seasons (Figure 3). The NUE of winter oilseed rape decreased with a rise in N rate from 80 kg ha^{-1} to 230 kg ha^{-1} (69.4 kg seeds per 1 kg N vs. 29.4 kg seeds per 1 kg N) (Table 5). The above decrease was particularly pronounced in hybrid cultivars (Artoga, PR D06), regardless of their growth habit (indeterminate, determinate) (Figure 4).

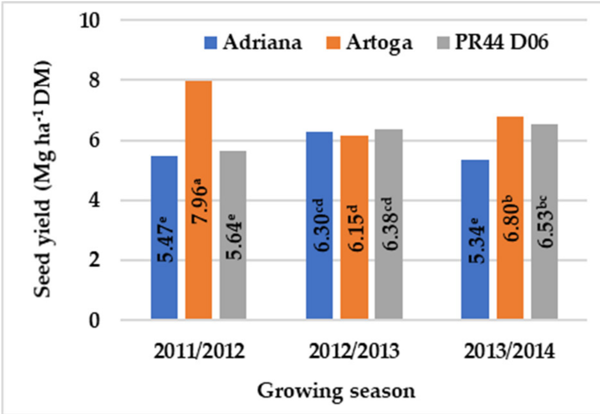

Figure 1. Seed yield of winter oilseed rape cultivars, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

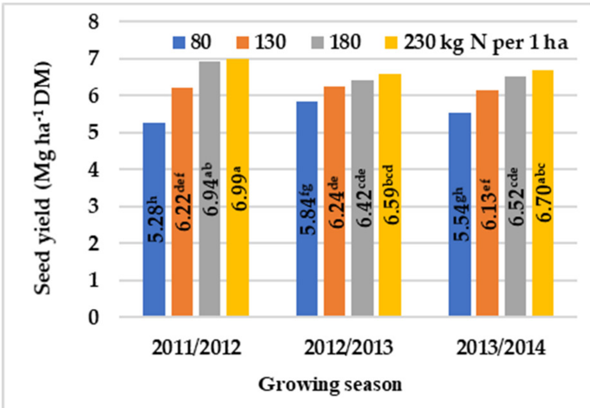

Figure 2. The effect of nitrogen (N) fertilization on the seed yield of winter oilseed rape, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

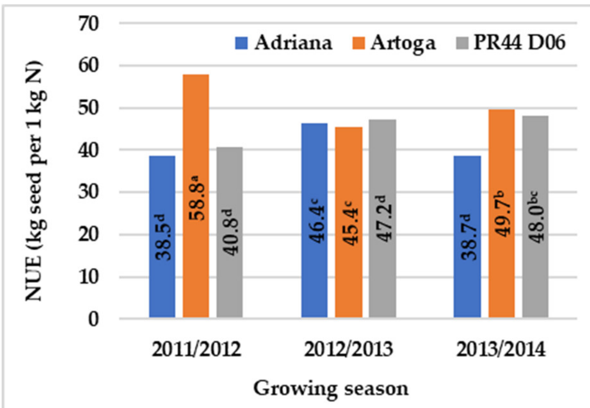

Figure 3. Nitrogen use efficiency of winter oilseed rape cultivars, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Regardless of cultivar, N rates higher than 180 kg ha^{-1} exerted a yield-forming effect only in combination with soil-applied S. In treatments supplied with high rates of N (180–230 kg N ha^{-1}), an increase in the N rate by 1 kg without supplementary S fertilization was not productive in any of the studied cultivars (Figure 5).

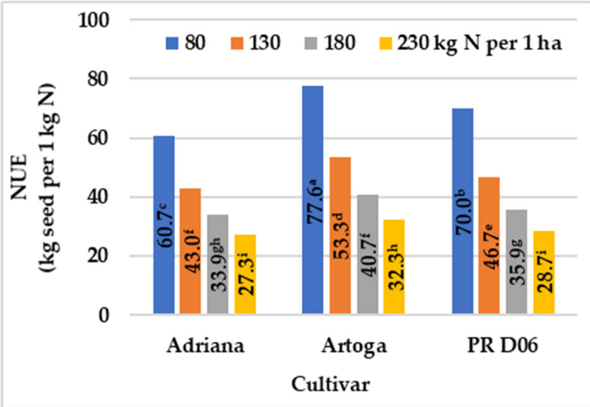

Figure 4. The effect of N rate on the nitrogen use efficiency of winter oilseed rape cultivars, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

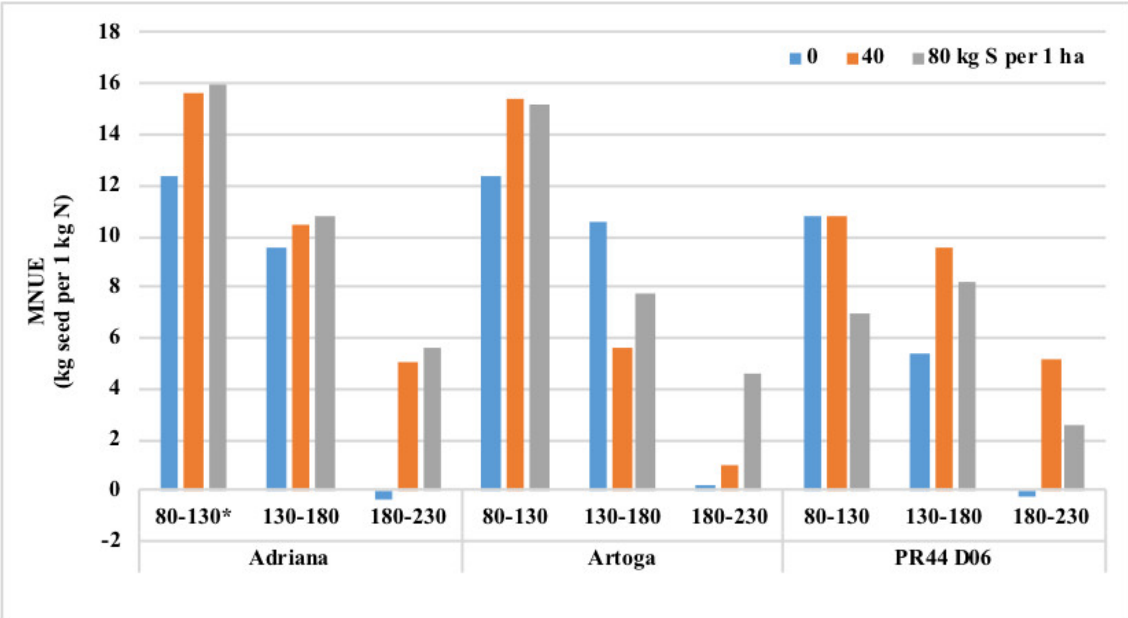

Figure 5. Marginal efficiency of N fertilization in winter oilseed rape cultivars in response to different S rates, across years. * N rate intervals.

As expected, straw yield was lowest (10.12 Mg ha^{-1}) in the semi-dwarf hybrid cultivar, moderate (10.54 Mg ha^{-1}) in the open-pollinated cultivar and highest (11.80 Mg ha^{-1}) in the long-stem hybrid cultivar (Table 5). The straw yield of the long-stem hybrid cultivar was particularly high (11.92 Mg ha^{-1}) in the first year of the experiment with above-average precipitation and a favorable rainfall pattern during the spring and summer growing seasons (Figure 6). Straw yield continued to increase up to the N rate of 130 kg N ha^{-1} (Table 5). Higher N rates (up to 230 kg N ha^{-1}) (Figure 7) increased straw yield only when the water requirements of plants were well met (year 1). Sulfur fertilization had no influence on straw yield (Table 3).

The ratio of seed yield to total biomass yield (harvest index) was higher in the semi-dwarf cultivar (0.347) than in long-stem cultivars (0.321–0.339). The harvest index of winter rapeseed increased up to the N rate of 180 kg ha^{-1} (Table 5). The influence of N fertilization on the harvest index was determined by weather conditions (Y × N interaction) and cultivar (Cv. × N interaction) (Table 3). In the dry year (year 3), an increase in N rates up to 230 kg ha^{-1} contributed to an increase in the harvest index (Figure 8). In the long-stem hybrid cultivar, the ratio of seed yield to straw yield was most desirable at the N rate of 130 kg ha^{-1}. In the open-pollinated cultivar and the semi-dwarf hybrid cultivar, the highest value of the harvest index was achieved at the N rate of 180 kg N ha^{-1} (Figure 9). The harvest index was not significantly affected by S fertilization (Table 3).

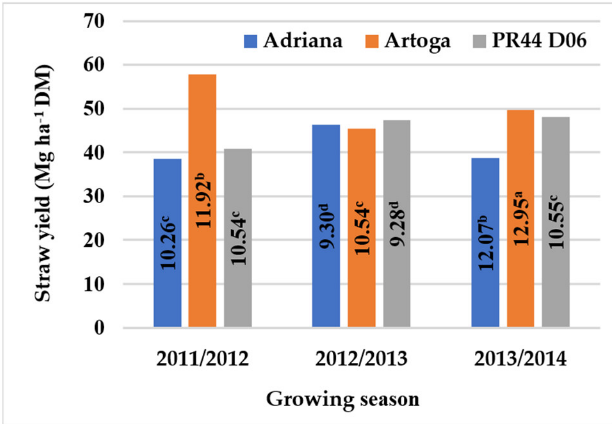

Figure 6. Straw yield of winter oilseed rape cultivars, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

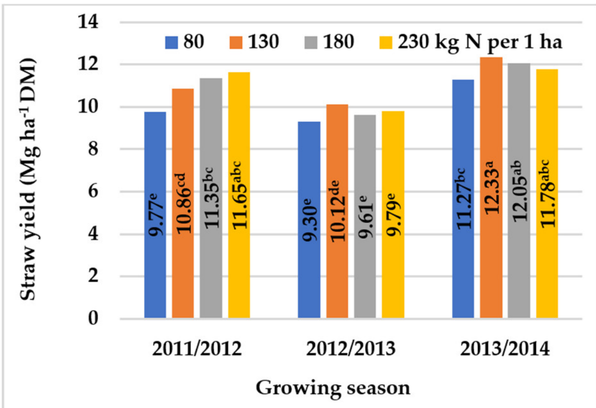

Figure 7. The effect of N rate on the straw yield of winter oilseed rape, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

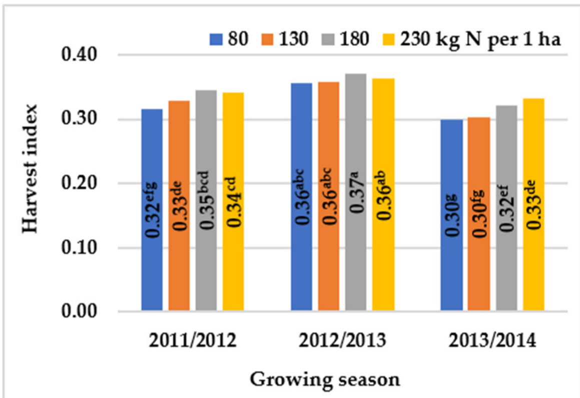

Figure 8. The effect of N rate on the harvest index of winter oilseed rape, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

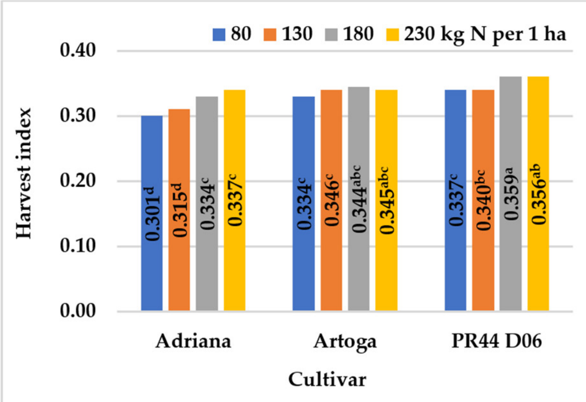

Figure 9. The effect of N rate on the harvest index of winter oilseed rape cultivars, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

3.3. Seed Quality

The crude fat content of seeds was higher in the open-pollinated cultivar and in the semi-dwarf hybrid cultivar (506–509 g crude fat kg^{-1} DM seeds). An increase in N rate decreased (by 2–5%) the crude fat content of seeds (Table 6) and the greatest decrease (5%) was noted in the semi-dwarf hybrid cultivar (Figure 10). The adverse effect of N fertilization on crude fat concentration was less pronounced when precipitation was low during the spring and summer growing seasons (year 3) (Figure 11). Spring S fertilization had no influence on the crude fat content of seeds in any of the analyzed cultivars (Table 3).

Table 6. Quality of winter oilseed rape seeds.

Parameter	Crude Fat (g kg^{-1} DM)	FAs (%)			Total Protein (g kg^{-1} DM)	GLS (µM g^{-1} DM)		LHV (MJ kg^{-1})
		$C_{18:1}$	$C_{18:2}$	$C_{18:3}$		Total	Alkenyl	
Growing Season								
2011/2013	503.6 ^{b}	62.1 ^{ab}	20.8 ^{ab}	10.4	178.5 ^{b}	11.8 ^{a}	8.3 ^{a}	25.2 ^{b}
2012/2013	513.6 ^{a}	62.4 ^{a}	20.6 ^{b}	10.3	173.4 ^{c}	12.0 ^{a}	8.4 ^{a}	25.7 ^{a}
2013/2014	493.6 ^{c}	61.8 ^{b}	20.9 ^{a}	10.6	184.0 ^{a}	11.4 ^{b}	8.1 ^{b}	25.7 ^{a}
Cultivar								
Adriana	505.5 ^{a}	63.2 ^{b}	20.4 ^{b}	9.8 ^{c}	180.8 ^{a}	12.6 ^{b}	9.3 ^{b}	25.6 ^{a}
Artoga	496.8 ^{b}	59.5 ^{c}	22.5 ^{a}	11.4 ^{a}	182.0 ^{a}	13.1 ^{a}	9.8 ^{a}	25.4 ^{b}
PRD06	508.5 ^{a}	63.7 ^{a}	19.4 ^{c}	10.2 ^{b}	173.2 ^{b}	9.4 ^{c}	5.6 ^{c}	25.6 ^{a}
Nitrogen Rate (kg ha^{-1}), across Years								
80	513.2 ^{a}	62.4 ^{ab}	20.7 ^{b}	10.2 ^{b}	171.6 ^{b}	12.1 ^{a}	8.6 ^{a}	25.6
130	503.6 ^{b}	62.6 ^{a}	20.5 ^{b}	10.3 ^{b}	174.9 ^{b}	11.6 ^{b}	8.1 ^{c}	25.5
180	503.2 ^{b}	61.7 ^{c}	21.1 ^{a}	10.6 ^{a}	182.6 ^{a}	11.2 ^{c}	7.9 ^{d}	25.5
230	494.3 ^{c}	61.8 ^{bc}	20.8 ^{ab}	10.7 ^{a}	185.7 ^{a}	11.9 ^{ab}	8.4 ^{b}	25.5
Sulfur Rate (kg ha^{-1}), across Years								
0	505.0	62.1	20.8	10.4	177.9	10.1 ^{c}	6.7 ^{c}	25.5
40	502.3	62.2	20.8	10.4	178.0	12.0 ^{b}	8.6 ^{b}	25.5
80	503.5	62.0	20.8	10.6	180.1	13.0 ^{a}	9.4 ^{a}	25.6

FAs—fatty acids; $C_{18:1}$—oleic acid; $C_{18:2}$—linoleic acid; $C_{18:3}$—linolenic acid; GLS—glucosinolates; LHV—lower heating value. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of letters denotes the non-significance of main effects.

The concentrations of major fatty acids (FAs) in the oil of winter oilseed rape reached 60–64% $C_{18:1}$, 19–23% $C_{18:2}$ and 10–11% $C_{18:3}$. The long-stem hybrid cultivar (Artoga) was least abundant in $C_{18:1}$ (59.5%) and most abundant in $C_{18:2}$ (22.5%) and $C_{18:3}$ (11.4%). Nitrogen fertilization contributed to an increase in $C_{18:1}$ (up to 130 kg N ha^{-1}) as well as $C_{18:2}$ and $C_{18:3}$ (up to 180 kg N ha^{-1}) levels (Table 6). The content of major FAs in the oil of winter oilseed rape was not significantly affected by S fertilization (Table 3).

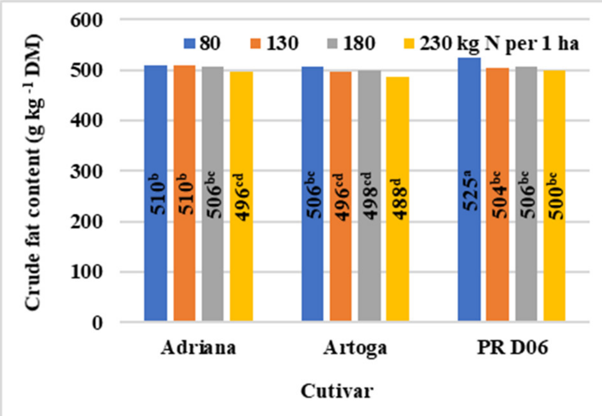

Figure 10. The effect of N rate on the crude fat content of winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

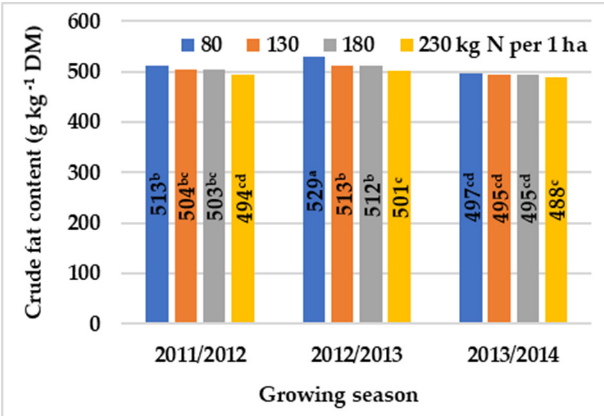

Figure 11. The effect of N rate on the crude fat content of winter oilseed rape seeds, across growing seasons (2011–2014). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The semi-dwarf hybrid cultivar (PR44 D06) accumulated significantly less total protein (by 7.6–8.8 g kg^{-1} DM) than long-stem cultivars (Adriana and Artoga). Nitrogen applied in spring up to the rate of 180 kg ha^{-1} increased total protein concentration in the seeds of winter oilseed rape by 6% (Table 6). The effect of N and S fertilization on total protein content varied across cultivars (Cv. × N and Cv. × S interactions) (Table 3). Nitrogen contributed to a greater increase in the total protein content of seeds in hybrid cultivars (13%) than in the open-pollinated cultivar (5%) (Figure 12). Protein synthesis increased (by 3%) under the influence of S fertilization only in long-stem cultivars (Adriana and Artoga). In the semi-dwarf hybrid cultivar (PR44 D06), S fertilization decreased total protein concentration by 2% (Figure 12).

Long-stem cultivars (Adriana and Artoga) accumulated 34–39% more GLS than the semi-dwarf hybrid cultivar (PR44 D06) (Table 6). In long-stem cultivars, N rates up to 180 kg ha^{-1} decreased GLS content by 7–8%, whereas higher N rates increased GLS content by 7–11%. The GLS content of seeds in the semi-dwarf hybrid cultivar was not significantly modified by N fertilization (Figure 13). Sulfur fertilization rates of 40 kg ha^{-1} and 80 kg ha^{-1} increased GLS levels by 19% and 29%, respectively (Table 6). The GLS content of seeds in long-stem cultivars increased up to the S rate of 80 kg S ha^{-1} and it was 1.4-fold higher in the hybrid cultivar than in the open-pollinated cultivar (2.6 µM g^{-1} DM vs. 3.7 µM g^{-1} DM). In the semi-dwarf cultivar, GLS levels continued to increase up to the S rate of

40 kg S ha^{-1} and were 30% lower than in long-stem cultivars (Figure 13). A significant interaction of N × S fertilization was found for the GLS content of winter oilseed rape seeds (Table 3). The S-induced increase in GLS levels was enhanced by growing rates of N fertilization (Figure 14). Therefore, N fertilization exacerbated the negative effects of S fertilization on the GLS content of all studied cultivars.

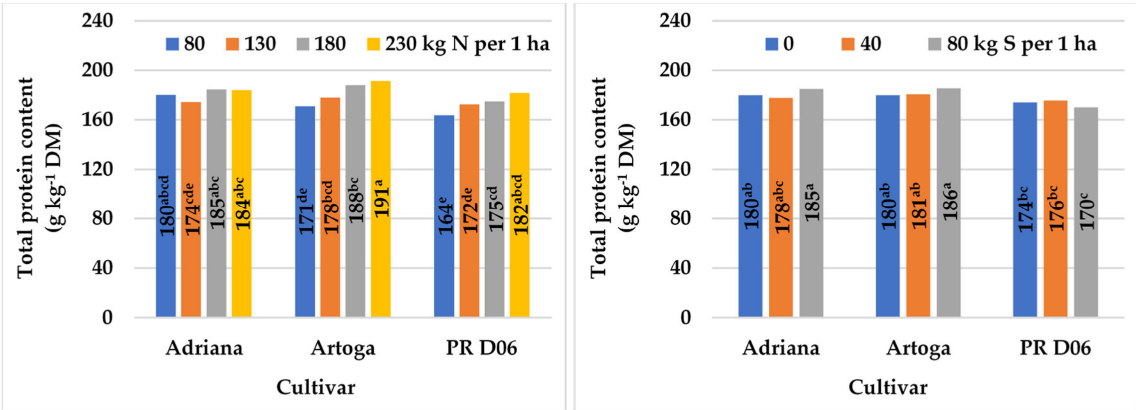

Figure 12. The effect of N and sulfur (S) rates on the total protein content of winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

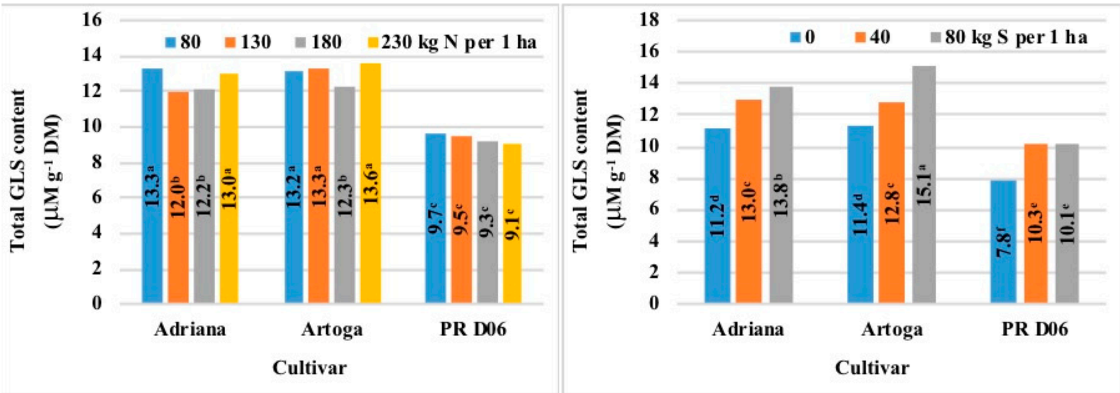

Figure 13. The effect of N and S rates on the total glucosinolates (GLS) content of winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

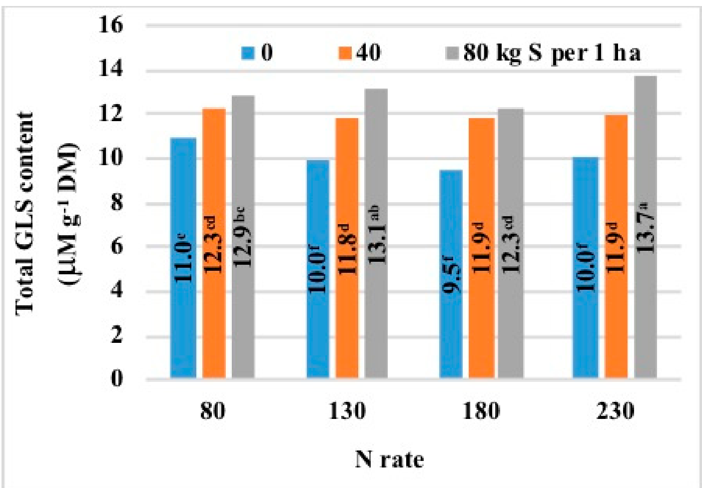

Figure 14. The relationship between N and S rates vs. the total GLS content of winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The content of alkenyl GLS in total GLS ranged from 60% in the semi-dwarf cultivar to 74–75% in long-stem cultivars. Long-stem cultivars accumulated 66–75% more alkenyl GLS than the semi-dwarf cultivar (9.3–9.8 µM g^{-1} DM vs. 5.6 µM g^{-1} DM). An increase in the N fertilizer rate to 180 kg ha^{-1} decreased the content of alkenyl GLS by 8% in all cultivars of winter oilseed rape (Table 6). An increase in the N fertilizer rate from 180 kg ha^{-1} to 230 kg ha^{-1} increased (by 6–11%) the content of alkenyl GLS in long-stem cultivars and induced a further drop (by 3–4%) in the analyzed parameter in the semi-dwarf cultivar (Figure 15). Sulfur fertilization rates of 40 kg ha^{-1} and 80 kg ha^{-1} increased the content of alkenyl GLS by 28% and 40%, respectively (Table 6). The increase in the S fertilizer rate from 40 kg ha^{-1} to 80 kg ha^{-1} did not cause an increase in alkenyl GLS levels only in the semi-dwarf cultivar (Figure 15). The S-induced increase in the concentrations of alkenyl GLS was further exacerbated by a rise in N rates in all cultivars (Figure 16).

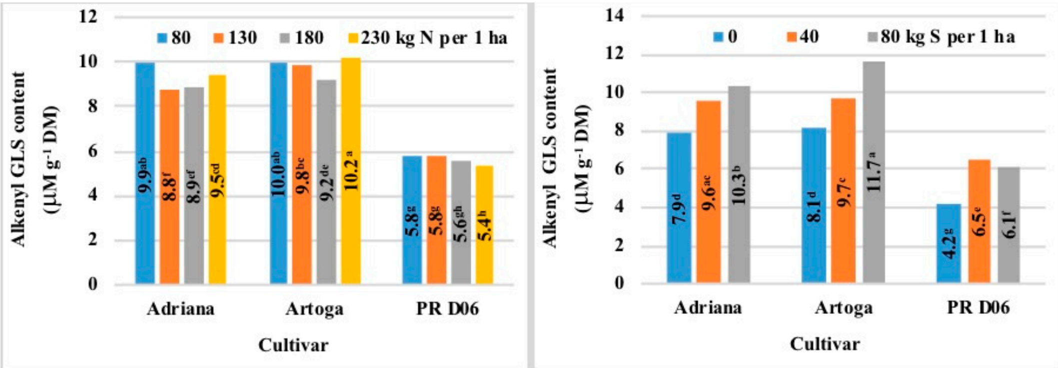

Figure 15. The effect of N and S rates on the content of alkenyl GLS in winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

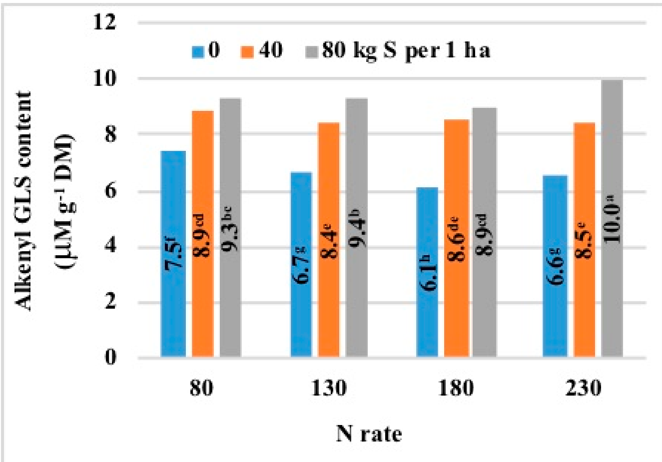

Figure 16. The relationship between N and S rates vs. the content of alkenyl GLS in winter oilseed rape seeds, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

The lower heating value (LHV) of winter rapeseed was weakly modified by the experimental factors. The above parameter was marginally higher (by 2%) in years with lower precipitation during the spring and summer growing seasons (years 2 and 3). Hybrid (long-stem and semi-dwarf) cultivars were characterized by significantly higher LHV (by 1%) than the open-pollinated cultivar (Table 6). Nitrogen and S fertilization did not differentiate LHV values in any of the studied cultivars (Table 3).

3.4. Economic Efficiency of Winter Rapeseed Production

The costs associated with the production of the open-pollinated cultivar ranged from €542–599 (≤130 kg N ha^{-1}) to €619–672 ha^{-1} (≥180 kg N ha^{-1}). Sulfur fertilization increased the production costs of the open-pollinated cultivar by up to ±3%. In hybrid cultivars, production costs were €25–28 (long-stem) and €21–25 ha^{-1} (semi-dwarf) higher on average than in the open-pollinated cultivar. The difference (3–5% on average) between the production costs of hybrid cultivars and the open-pollinated genotype had no significant effect on cost structure. Mineral fertilizers accounted for 37–43% (≤130 kg N ha^{-1}) to 47–49% (≥180 kg N ha^{-1}) of total production costs in all cultivars (Tables 7–10).

All cultivars of winter oilseed rape generated revenues and high profits in NE Poland. The long-stem hybrid cultivar (Artoga) was most economically effective, followed by the semi-dwarf hybrid cultivar (PR44 D06) and the open-pollinated cultivar (Adriana) (Table 10). In each of the analyzed cultivars, seed production value and revenue were highest in the production technology with fertilizer rates of 230 kg N ha^{-1} and 40 kg S ha^{-1}. The influence of N and S fertilizer rates varied across cultivars. The production technology involving 180 kg N ha^{-1} and 40 kg S ha^{-1} maximized the profitability of the open-pollinated cultivar (358%) and the semi-dwarf hybrid cultivar (368%). In the long-stem hybrid cultivar (Artoga), profitability peaked (419%) in response to a lower N rate (130 kg N ha^{-1}) supplemented with 40 kg S ha^{-1} (Table 10).

Table 7. Production costs of the open-pollinated cultivar of winter oilseed rape (cv. Adriana), across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Production costs (€ ha^{-1}), including:	542	553	561	580	591	599	619	629	637	652	664	672
Tillage	100	100	100	100	100	100	100	100	100	100	100	100
Sowing	70	70	70	70	70	70	70	70	70	70	70	70
Mineral fertilizers	201	211	219	235	245	253	272	282	290	306	316	324
Weed control	75	75	75	75	75	75	75	75	75	75	75	75
Pest control	50	50	50	50	50	50	50	50	50	50	50	50
Harvest and transport	46	47	47	50	51	51	52	52	52	51	52	53

Table 8. Production costs of the long-stem hybrid cultivar of winter oilseed rape (cv. Artoga), across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur Rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Production costs (€ ha^{-1}), including:	569	581	586	605	616	624	645	655	663	679	689	697
Tillage	100	100	100	100	100	100	100	100	100	100	100	100
Sowing	90	90	90	90	90	90	90	90	90	90	90	90
Mineral fertilizers	201	211	219	235	245	253	272	282	290	306	316	324
Weed control	75	75	75	75	75	75	75	75	75	75	75	75
Pest control	50	50	50	50	50	50	50	50	50	50	50	50
Harvest and transport	53	54	52	54	55	55	57	57	57	57	57	57

3.5. Energy Efficiency of Winter Rapeseed Production

The demand for energy in the production of winter rapeseed ranged from 14.5–19.3 (≤130 kg N ha^{-1}) to 22.4–27.0 GJ ha^{-1} (≥180 kg N ha^{-1}) (Tables 11–13). The energy demand of all winter oilseed rape cultivars increased by 26% (130 kg N ha^{-1}), 52–53% (180 kg N ha^{-1}) and 78–79% (230 kg N ha^{-1}) when

N fertilizer was applied at rates higher than 80 kg ha^{-1}. Cultivar differentiated energy demand by up to ±0.5% in all production technologies. The variation in energy demand in response to S fertilization did not exceed ±4%. Mineral fertilization accounted for 75–86% of total energy inputs in the production of the evaluated winter rapeseed cultivars. The proportions of the remaining agronomic operations in the structure of energy inputs were determined at—tillage—6–11%, harvest—4–8%, weed and pest control—3–5% and sowing—1–2% (Tables 11–13).

The energy output and energy gain in the production of open-pollinated and semi-dwarf cultivars were highest in the production technology where N and S fertilizers were applied at 230 kg N ha^{-1} and 40 kg S ha^{-1} (Table 14). In the production of the long-stem hybrid cultivar, energy output peaked in response to the highest fertilization levels (230 kg N ha^{-1}, 80 kg S ha^{-1}), whereas the highest energy gain was noted in response to the lowest N rate (180 kg N ha^{-1}) without S fertilization. In all tested cultivars, energy efficiency was highest in the low-input production technology with an N fertilizer rate of 80 kg N ha^{-1} and no S fertilization (Table 14). All winter oilseed rape cultivars were characterized by a positive energy balance and high energy efficiency. However, energy output (173.2 GJ ha^{-1}), energy gain (149.0 GJ ha^{-1}) and energy efficiency (10.14) were highest in the long-stem hybrid cultivar. The average energy efficiency of the semi-dwarf hybrid cultivar and the open-pollinated cultivar was 10% and 18% lower, respectively (Table 14).

Table 9. Production costs of the semi-dwarf hybrid cultivar of winter oilseed rape (cv. PR44 D06), across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur Rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Production costs (€ ha^{-1}), including:	567	576	584	603	614	621	642	652	660	677	688	694
Tillage	100	100	100	100	100	100	100	100	100	100	100	100
Sowing	91	91	91	91	91	91	91	91	91	91	91	91
Mineral fertilizers	201	211	219	235	245	253	272	282	290	306	316	324
Weed control	75	75	75	75	75	75	75	75	75	75	75	75
Pest control	50	50	50	50	50	50	50	50	50	50	50	50
Harvest and transport	49	48	48	52	52	52	53	53	53	54	55	53

Table 10. Economic efficiency of the analyzed winter oilseed rape cultivars, across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur Rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Cv. Adriana												
Production value (€ ha^{-1})	1749	1782	1753	1974	2065	2043	2148	2254	2239	2141	2344	2341
Revenue (€ ha^{-1})	1207	1229	1192	1394	1474	1444	1529	1624	1602	1489	1681	1668
Profitability index (%)	323	322	313	341	349	341	347	358	351	328	353	348
Cv. Artoga												
Production value (€ ha^{-1})	2265	2301	2192	2490	2580	2468	2682	2682	2609	2686	2700	2693
Revenue (€ ha^{-1})	1695	1720	1605	1885	1964	1844	2037	2027	1946	2007	2011	1996
Profitability index (%)	398	396	374	412	419	396	416	409	394	396	392	386
Cv. PR44 D06												
Production value (€ ha^{-1})	2032	2029	2036	2228	2225	2163	2326	2399	2312	2323	2493	2359
Revenue (€ ha^{-1})	1466	1453	1452	1625	1611	1541	1685	1747	1652	1646	1805	1665
Profitability index (%)	359	352	349	369	362	348	363	368	351	343	362	340

Table 11. Energy inputs in the production of the long-stem open-pollinated cultivar of winter oilseed rape (cv. Adriana), across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur Rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Energy inputs (MJ ha^{-1}), including:	14,480	14,896	15,252	18,411	18,834	19,190	22,352	22,751	23,107	26,178	26,601	26,981
Tillage	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623
Sowing	247	247	247	247	247	247	247	247	247	247	247	247
Mineral fertilizers	10,955	11,353	11,709	14,805	15,203	15,559	18,697	19,095	19,451	22,547	22,945	23,301
Weed control	373	373	373	373	373	373	373	373	373	373	373	373
Pest control	324	324	324	324	324	324	324	324	324	324	324	324
Harvest and transport	957	975	975	1038	1063	1063	1087	1087	1087	1063	1087	1112

Table 12. Energy inputs in the production of the long-stem hybrid cultivar of winter oilseed rape (cv. Artoga), across years.

Parameter	Nitrogen Rate (kg ha^{-1})											
	80			130			180			230		
	Sulfur Rate (kg ha^{-1})											
	0	40	80	0	40	80	0	40	80	0	40	80
Energy inputs (MJ ha^{-1}), including:	14,602	15,025	15,337	18,477	18,900	19,256	22,439	22,837	23,193	26,289	26,687	27,043
Tillage	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623
Sowing	220	220	220	220	220	220	220	220	220	220	220	220
Mineral fertilizers	10,955	11,353	11,709	14,805	15,203	15,559	18,697	19,095	19,451	22,547	22,945	23,301
Weed control	373	373	373	373	373	373	373	373	373	373	373	373
Pest control	324	324	324	324	324	324	324	324	324	324	324	324
Harvest and transport	1107	1132	1087	1132	1157	1157	1201	1201	1201	1201	1201	1201

Table 13. Energy inputs in the production of semi-dwarf hybrid cultivar of winter oilseed rape (cv. PR44 D06), across years.

Parameter	**Nitrogen Rate (kg ha^{-1})**											
	80			**130**			**180**			**230**		
	Sulfur Rate (kg ha^{-1})											
	0	**40**	**80**	**0**	**40**	**80**	**0**	**40**	**80**	**0**	**40**	**80**
Energy inputs (MJ ha^{-1}), including:	14,526	14,900	15,256	18,433	18,831	19,187	22,350	22,748	23,104	26,219	26,642	26,954
Tillage	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623	1623
Sowing	220	220	220	220	220	220	220	220	220	220	220	220
Mineral fertilizers	10,955	11,353	11,709	14,805	15,203	15,559	18,697	19,095	19,451	22,547	22,945	23,301
Weed control	373	373	373	373	373	373	373	373	373	373	373	373
Pest control	324	324	324	324	324	324	324	324	324	324	324	324
Harvest and transport	1031	1007	1007	1087	1087	1087	1112	1112	1112	1132	1157	1112

Table 14. Energy efficiency of the analyzed winter oilseed rape cultivars, across years.

Parameter	**Nitrogen Rate (kg ha^{-1})**											
	80			**130**			**180**			**230**		
	Sulfur Rate (kg ha^{-1})											
	0	**40**	**80**	**0**	**40**	**80**	**0**	**40**	**80**	**0**	**40**	**80**
Cv. Adriana												
Energy output (GJ ha^{-1})	113.1	114.1	114.8	128.7	133.9	132.4	139.3	145.6	145.4	139.4	152.6	151.7
Energy gain (GJ ha^{-1})	98.5	99.2	99.5	110.3	115.0	113.2	117.0	122.8	122.3	113.2	126.0	124.7
Energy efficiency ratio	7.79	7.66	7.53	6.99	7.11	6.90	6.23	6.40	6.29	5.33	5.74	5.62
Cv. Artoga												
Energy output (GJ ha^{-1})	148.1	147.9	140.6	159.9	165.7	158.8	171.5	171.6	169.1	172.6	172.0	173.2
Energy gain (GJ ha^{-1})	133.5	132.9	125.3	141.4	146.8	139.5	149.0	148.8	145.9	146.3	145.3	146.2
Energy efficiency ratio	10.14	9.84	9.17	8.65	8.77	8.24	7.64	7.51	7.29	6.57	6.45	6.40
Cv. PR44 D06												
Energy output (GJ ha^{-1})	132.1	131.9	132.9	144.1	142.4	141.1	150.4	156.2	150.7	151.2	161.4	153.1
Energy gain (GJ ha^{-1})	117.5	117.0	117.7	125.7	123.6	121.9	128.0	133.4	127.6	125.0	134.8	126.2
Energy efficiency ratio	9.09	8.85	8.71	7.82	7.56	7.35	6.73	6.87	6.52	5.77	6.06	5.68

4. Discussion

4.1. Biomass Yield and the Harvest Index

Rapeseed cultivars represent genetic progress and they are the most important and the cheapest factors in the crop production technology. The agricultural performance of winter oilseed rape cultivars differs significantly. In Europe, the yields of hybrid cultivars are approximately 7–9% [8] or even 13% higher compared with the yields of open-pollinated cultivars [9]. The introduction of cultivars resistant to clubroot [127] and imazamox (CL) [128], and the development of semi-dwarf cultivars of winter oilseed rape [129], were important milestones in agricultural production in the last decade. The yields of semi-dwarf cultivars of winter oilseed rape are generally 1–7% [9,10,130,131] to 9–18% [10,130,132,133] lower in comparison with cultivars with a conventional growth habit. In semi-dwarf cultivars, lower yields result from a smaller (by 24–31%) number of seeds per silique [132] or a smaller (by 6–18%) number of seeds per silique and lower (by 3–6%) 1000-seed weight [10,134]. The yields of semi-dwarf cultivars approximate those noted in morphotypes with a conventional growth habit under conditions that do not support the achievement of their full yield potential [21] and under unfavorable thermal conditions in winter [10]. In the present experiment conducted in NE Poland, weather conditions promoted high and stable yields (6.2–6.4 Mg ha^{-1}). Under favorable conditions, the yield of the semi-dwarf hybrid cultivar was 11% lower (0.79 Mg ha^{-1}) than in the long-stem hybrid cultivar but 8% higher (0.48 Mg ha^{-1}) than in the open-pollinated cultivar. Similar relationships between the yields of open-pollinated and hybrid cultivars with an indeterminate and determinate growth habit were reported by Gugała et al. [133] in central-eastern Poland.

Semi-dwarf cultivars of winter rapeseed are less susceptible to lodging and are characterized by a higher harvest index [23]. In a study conducted by Miersch et al. [23] in Central Germany (Lower Saxony), the seed yield to straw yield ratio (harvest index) of 108 hybrids (54 normal-type and 54 semi-dwarf hybrids) was significantly higher in semi-dwarf hybrids (0.410–0.460) than in normal-type hybrids (0.340–0.410). In the present experiment, the harvest index was also higher in the semi-dwarf cultivar (0.347) than in long-stem cultivars (0.321–0.339). Contrary results were reported in a study by Jankowski et al. [10], where semi-dwarf cultivars produced shorter but more branched stems and formed a higher number of productive siliques than the long-stem cultivar [10]. The harvest index was also higher in long-stem cultivars than in semi-dwarf cultivars of winter oilseed rape in the work of Gugała et al. [133] and Dresbøll et al. [135].

Research into double-low cultivars of conventional winter oilseed rape demonstrated the positive effects of spring N fertilization at 150–180 kg N ha^{-1} [10,136,137]. In high-input production technologies, yields improved in response to N fertilization rates of 200–250 kg N ha^{-1} [10,26,44,138–141] or even 300 kg ha^{-1} [70,142]. Miersch et al. [23] demonstrated that yields were 9% higher in semi-dwarf hybrids than in normal-type hybrids (2.24 Mg ha^{-1} vs. 2.05 Mg ha^{-1}) when nitrogen supply was low, whereas no differences in yield were observed between cultivars when nitrogen supply was high. Kessel et al. [30] also reported differences in NUE between open-pollinated and hybrid cultivars. Despite the above, a significant interaction of cultivar and N rate for seed yield is difficult to prove [30,44,143–145]. Differences in the development of long-stem and semi-dwarf cultivars of winter oilseed rape are manifested mainly in fall and early spring [146]. At the end of flowering, differences between cultivars generally disappear and their harvest index reaches similar values [10,133,135]. For this reason, long-stem and semi-dwarf cultivars can respond similarly to N fertilization [10,130,132,133]. In the current study, N fertilizer applied at a rate of up to 180 kg ha^{-1} exerted a yield-forming effect in all winter oilseed rape cultivars. In all tested cultivars, the yield-forming effect of the highest N rate (230 kg ha^{-1}) was observed only during the spring and summer growing seasons with low precipitation. The strong impact of environmental and climatic conditions on the yield-forming potential of N fertilizer applied in spring was also described by Jankowski et al. [10]. Nitrogen rates exceeding 180 kg ha^{-1} exerted no yield-forming effect when the water requirements of winter oilseed rape were fully met in spring. In years with low rainfall in spring, N fertilizer rates up to 240 kg ha^{-1} improved yields in all analyzed cultivars [10]. In a study by Litke et al. [26], weather conditions also significantly differentiated the yield-forming effects of N fertilization across growing seasons. The seed yield of winter oilseed rape supplied with 240 kg N ha^{-1} ranged from 1.8 Mg ha^{-1} to 6.8 Mg ha^{-1}.

According to Cheema et al. [147], the harvest index increases with a rise in N fertilization rate until the achievement of maximum seed yield. The harvest index is lower when the N rate exceeds the rate required for maximum seed yield. In a study by Dresbøll et al. [135], an increase in the N fertilization rate from 120 kg N ha^{-1} to 280 kg N ha^{-1} increased the harvest index in the semi-dwarf cultivar (from 0.340 to 0.375) and the long-stem cultivar (from 0.355 to 0.385). In the work of Miersch et al. [23], the harvest index of both semi-dwarf and normal-type hybrids was higher in production technologies characterized by high (0.410–0.460) than low N supply (0.340–0.410). Jankowski et al. [10] found that the harvest index of winter oilseed rape peaked in response to the N rate of 180 kg ha^{-1}. A further increase in N rate (240 kg ha^{-1}) caused a marginal decrease in the value of the harvest index (N rates higher than 180 kg N ha^{-1} were more likely to stimulate straw yield than seed yield) [10]. In the present experiment, the harvest index of winter oilseed rape also increased up to the N rate of 180 kg ha^{-1}. However, the yield-forming effect of N fertilization varied across cultivars. The harvest index of the long-stem hybrid cultivar peaked in response to the N rate of 130 kg N ha^{-1}. The highest increase in the harvest index of the open-pollinated (long-stem) cultivar and the semi-dwarf hybrid cultivar was noted when the N rate was increased to 180 kg ha^{-1}. These findings indicate that N rates exceeding 130 kg ha^{-1} exerted more stimulatory effects on seed yield than straw yield only in the open-pollinated cultivar and the semi-dwarf hybrid cultivar.

The S requirements of oilseed rape range from 1.5 to 2.0 kg S 100 kg^{-1} of seeds [148,149]. Seed yields increase considerably in response to S fertilization when S levels are low in soil and plants. The lower the availability of S for plants, the greater the S-induced increase in yields [32,43,45,150,151]. In the experiments conducted by Withers et al. [36] and Bilsborrow et al. [37], oilseed rape yields increased by 15–74% and were highest (65% higher than in the control treatment) in soils deficient in SO_4^{2-} and at S fertilizer rate of 40 kg ha^{-1}. In soils with moderate SO_4^{2-} levels, S fertilization increased oilseed rape yields by up to 10%. Jankowski [44] demonstrated that the yield-forming effect of S fertilization was strongly correlated with environmental and climatic conditions. The yield-forming effect of S fertilization was weak in soils relatively abundant in SO_4^{2-} and in years with above-average precipitation in fall. High S rates (90 kg ha^{-1}) improved yields in soils deficient in SO_4^{2-} and in a year with heavy precipitation in late fall [44]. In the present experiment, established on soil with low and moderate levels of SO_4^{2-}, S fertilization exerted a weak yield-forming effect (seed yield increased by 3% in response to the S rate of 40 kg ha^{-1}).

Zukalová et al. [152] demonstrated that the genetic factor significantly influences the effectiveness of S fertilization. The demand for S fertilizer was higher in low-yielding cultivars. The optimal S rate in the cultivation of a genetically modified (highest yielding) cultivar was determined at 40 kg ha^{-1}. The S-induced increase in the seed yield of less productive (open-pollinated and hybrid) cultivars was 2–4 lower than the corresponding increase in the seed yield of the transgenic cultivar and it required higher S supply (80 kg ha^{-1}). In a study by Jankowski [44], S fertilization induced a significant increase in seed yield only in the cultivar with a lower yield potential (open-pollinated). The yield of the more productive hybrid cultivar did not increase in response to S fertilization, In contrast, Wielebski and Wójtowicz [153] found that S fertilization increased yields in both open-pollinated and hybrid cultivars. In the current study, all of the tested winter oilseed rape cultivars responded similarly to S fertilization.

Sulfur plays a particularly important role in N metabolism by accelerating the conversion of plant-absorbed N into protein [154]. Sulfur increases seed yields mainly by improving the N balance in plants [42,85]. Balanced fertilization of winter oilseed rape is essential for maximizing productivity (seed yield) and profits [42]. The interaction effects of S and N on rapeseed yields have been long recognized [42,45,80]. In a study by Jankowski [44], high N rates (240 kg ha^{-1}) exerted a yield-forming effect only in combination with an S fertilizer rate of 30 kg ha^{-1}. A correlation between the agronomic effectiveness of high N rates and S fertilization was also noted in alternative *Brassica* crops [50,54,80].

According to Fismes et al. [55], N and S exert synergistic effects if both elements are optimally balanced and antagonistic effects if one of the elements occurs in excess. Seed yields can decrease in S-deficient plants supplied with high N rates because non-protein N exerts toxic effects on plants [87]. In the present experiment, N rates higher than 180 kg ha^{-1} exerted a yield-forming effect only in combination with S fertilization. In production technologies with high N rates (180–230 kg N ha^{-1}), the increase in the N rate by 1 kg without supplementary S fertilization was unproductive in all cultivars of winter oilseed rape.

Sulfur fertilization generally improves the ratio of seed yield to total biomass yield in *Brassica* crops. In the work of Ahmad et al. [155] and Fazili et al. [41], the S rate of 40 kg S ha^{-1} increased the harvest index of field mustard (*Brassica rapa* L.) from 0.317 to 0.335 and from 0.265 to 0.345, respectively. In a study by Piri [156], the harvest index of black mustard (*Brassica nigra* L.) increased from 24% to 29% in response to the application of 45 kg S ha^{-1}. In experiments conducted in NE Poland, S fertilization did not differentiate the harvest index of camelina [50]. In the current study, S fertilization did not cause differences in the harvest index of the tested winter oilseed rape cultivars.

4.2. Seed Quality

In a study of registered crop varieties conducted by the Polish Research Center for Cultivar Testing (COBORU), the average content of crude fat and total protein in the seeds of 25 open-pollinated cultivars grown in 2016–2018 was determined at 466–500 g kg^{-1} DM and 354–396 g kg^{-1} DM, respectively [9]. Nutrient concentrations in the seeds of 94 hybrid cultivars grown in the same period were 3 g kg^{-1} DM (crude fat) and 4 g kg^{-1} DM (total protein) lower than in the seeds of open-pollinated cultivars. In 2016–2018, the semi-dwarf cv. Thure (the only semi-dwarf variety examined by COBORU) accumulated 11 g kg^{-1} DM less crude fat than long-stem hybrids [9]. The semi-dwarf cultivar was also less abundant in crude fat in the present experiment. In a study conducted in Czechia, the crude fat content of semi-dwarf cultivars of winter oilseed rape was determined at 432–472 g kg^{-1} DM and was 1% and 2% higher on average than in hybrid and open-pollinated cultivars, respectively [157]. In Central Germany (Lower Saxony), semi-dwarf and normal-type hybrids of winter oilseed rape accumulated similar amounts of crude fat (496–500 g kg^{-1} DM) and total protein (183–184 g kg^{-1} DM) [23].

Glucosinolate levels are an important parameter in winter rapeseed processing, in particular in feed production. Open-pollinated cultivars registered in Poland accumulate around 8.6–14.4 µM of GLS g^{-1} seeds. Glucosinolate concentrations are around 5–6% higher in hybrid than in open-pollinated cultivars. The semi-dwarf cultivar of winter oilseed rape tested by COBORU contained approximately 1% more GLS in seeds than long-stem hybrid cultivars [59]. Research conducted in Poland outside COBORU stations also demonstrated that GLS content was 2–3% higher in semi-dwarf than in long-stem cultivars of winter oilseed rape [158,159]. In contrast, Ratajczak et al. [129] found that GLS levels were 13% lower in the semi-dwarf cultivar than in long-stem hybrid and open-pollinated cultivars. In the present study, both long-stem cultivars of winter oilseed rape also accumulated 34–39% more GLS than the semi-dwarf hybrid cultivar. The content of undesirable alkenyl GLS was significantly higher in long-stem cultivars than in the semi-dwarf cultivar (74–75% vs. 60%). The concentration and qualitative composition of GLS in the seeds of the semi-dwarf hybrid indicate that this cultivar is more suitable for the production of feed than long-stem hybrid and open-pollinated cultivars.

High N fertilization rates in spring decrease the crude fat content and increase the total protein content of winter oilseed rape. The above relationships have been observed in all rapeseed types, including long-stem cultivars with high EA and GLS content [160], canola-quality cultivars with low EA and GLS content [61,64,80,147] and HEAR lines with high EA content and low GLS content [161]. Similar correlations between N fertilization vs. crude fat and total protein content were reported in many *Brassica* crops, including camelina [50], brown mustard [68] and white mustard [53,54]. In the present study, N fertilization also increased the crude fat content and decreased the total protein content of winter oilseed rape. The N-induced changes in the concentrations of the above nutrients varied across cultivars. Higher N rates provoked a greater decrease in the crude fat content of the semi-dwarf cultivar than long-stem cultivars (5% vs. 3%). The N-induced increase in total protein concentration was nearly three-fold higher in both hybrid cultivars than in the open-pollinated cultivar (13% vs. 5%). In a study by Miersch et al. [23], crude fat accumulation was highly similar in semi-dwarf and long-stem hybrids (495 g kg^{-1} DM and 500 g kg^{-1} DM, respectively) supplied with low N rates. Semi-dwarf cultivars accumulated less crude fat than long-stem cultivars (466 g kg^{-1} DM vs. 476 g kg^{-1} DM) in response to high N supply.

Nitrogen fertilization also influences the content and qualitative composition of GLS. In the works of Bilsborrow et al. [70] and Narits [61], the total GLS content of rapeseed increased up to 140–150 kg N ha^{-1} and was stabilized at higher rates. Zhao et al. [74] and Zhao et al. [139] reported an increase in the GLS content of rapeseed up to N rates of 240–300 kg N ha^{-1}. However, Wójtowicz et al. [162] and Wójtowicz et al. [163] found that an increase in the spring rate of N from 60 to 220 kg ha^{-1} did not differentiate GLS levels in oilseed rape. In the present experiment, N fertilization exerted a positive effect on the content and qualitative composition of GLS in the semi-dwarf cultivar. In long-stem cultivars (hybrid and open-pollinated), total GLS concentrations and the content of alkenyl GLS continued to decrease up to the N rate of 180 kg ha^{-1}. In the above cultivars, total GLS concentrations and the content of alkenyl GLS increased in response to higher rates (>180 kg N ha^{-1}) of N fertilization.

The absence of plant-available S generally inhibits the biosynthesis of total protein in oilseed rape, which was observed in traditional cultivars (high-EA and high-GLS) [164], canola-quality cultivars [80,81,83] and alternative *Brassica* crops, including *B. juncea* canola [151], *B. juncea* mustard [151,165], *C. sativa* [48] and *S. alba* [54,166]. In the current study, the S-induced increase in total protein content was noted only in long-stem cultivars (open-pollinated and hybrid). Sulfur fertilization decreased total protein concentration in the seeds of the semi-dwarf cultivar.

Sulfur fertilization exerts varied effects on the crude fat content of winter oilseed rape seeds [34]. Differences in the crude fat content of *Brassica* crops, including *B. campestris* [167], *C. sativa* [48,50], *B. juncea* and *S. alba* [34], were also noted in response to S fertilization. In the present experiment, the application of S did not affect crude fat concentrations in winter oilseed rape. Sulfur fertilization had no influence on the crude fat content of rapeseed in the works of Filipek-Mazur et al. [47], Ijaz and Honermeier [57], Šiaudinis and Butkutė [38] and Jankowski et al. [34]. In turn, Jankowski et al. [83], Čeh et al. [168] and Sardana and Atwal [169] observed a decrease in the crude fat content of rapeseed supplied with S. Crude fat levels in rapeseed increased in response to S fertilization in Pakistan [80], Iran [81], central and southern Poland [82], China [170] and France [64].

Sulfur fertilizers can compromise the quality of seeds in canola cultivars of winter rapeseed by increasing their total GLS content by 7% [171], 14–37% [34,56,83] (Table 6) or even 50–80% [56,80]. The adverse impact of S fertilization on GLS levels is generally stronger in hybrids than in open-pollinated cultivars [44]; Figure 13 and in plants supplied with high rates of N [44]; Figure 14. Sulfur stimulates primarily the biosynthesis of alkenyl GLS [34,79,172], which compromises the nutritional value of non-fat seed residues [173]. Sulfur enhances the synthesis of methionine which acts as a precursor for alkenyl GLS [60]. In the present experiment, higher S rates increased the content of alkenyl GLS by 28–41% only in long-stem cultivars (with a higher concentration of alkenyl GLS). In the semi-dwarf cultivar (with a low content of alkenyl GLS), the accumulation of GLS was low even in response to a high S fertilization rate (80 kg ha^{-1}). The detrimental effects of S on winter rapeseed cultivars with a higher content of alkenyl GLS were also observed by Wielebski [174]. In turn, Rotkiewicz et al. [175] and Jankowski [44] reported a stronger correlation between S fertilization and the concentration of alkenyl GLS in rapeseed cultivars with a lower GLS content.

4.3. Economic Efficiency of Winter Rapeseed Production

Economic efficiency, defined as the difference between agricultural inputs and outputs, is a very important consideration in crop production. Only farms where revenues exceed costs are able to grow and build a competitive advantage on the agricultural market [103]. A study conducted by

Nilsson et al. [104] in Northern and Central Europe (United Kingdom, Germany, Poland, Estonia, Sweden) demonstrated that traditional (high-input) winter rapeseed production technologies were characterized by the highest economic efficiency but also by the highest production costs. The costs associated with the production of winter rapeseed in the high-input technology were estimated at €800–1000 ha^{-1} in Germany, €700–800 ha^{-1} in the United Kingdom, €600–700 ha^{-1} in Sweden and €550–580 ha^{-1} in Poland. The relevant costs were lower by €100–150 ha^{-1} on average in the integrated (medium-input) technology [104]. Sokólski et al. [120] also argued that the production technology of winter oilseed rape should be optimized for specific cultivars (morphotypes) to maximize profitability. According to Chiriac et al. [21], cultivars with different yield potential generate different costs in identical production technologies. In the work of Sokólski et al. [120], the costs associated with the high-input production technology of winter oilseed rape seeds ranged from €861–910 ha^{-1} (semi-dwarf cultivars) to €956 ha^{-1} (long-stem cultivar). In the current study, the costs associated with the production of the open-pollinated cultivar (Adriana) ranged from €542–599 (≤130 kg N ha^{-1}) to €619–672 ha^{-1} (≥180 kg N ha^{-1}). Production costs were 4% higher in hybrid cultivars (semi-dwarf and long-stem) than in the open-pollinated cultivar. Sulfur fertilization increased production costs by up to ±3% in all analyzed cultivars of winter oilseed rape. Economic efficiency was highest in the long-stem hybrid cultivar (Artoga), followed by the semi-dwarf hybrid cultivar (PR44 D06) and the open-pollinated cultivar (Adriana). Long-stem hybrids should be grown in high-input technologies (230 kg N ha^{-1} and 40 kg S ha^{-1}) in small-area farms where production is limited mainly by access to land (highest revenue per ha). However, when the key limiting factor is the availability of energy resources rather than land (large-area farms), the energy efficiency of long-stem hybrids is expected to be higher in low-input technologies (130 kg N ha^{-1} and 40 kg S ha^{-1}).

4.4. Energy Efficiency of Winter Rapeseed Production

In Europe, energy consumption in rapeseed production ranges from 13 35 GJ ha^{-1} to 35 GJ ha^{-1}, depending on agricultural intensity [108,176–178]. In a study conducted in a large-area farm in NE Poland, the energy inputs associated with the cultivation of winter oilseed rape reached 29–32 GJ ha^{-1} in the high-input technology, 21–24 GJ ha^{-1} in the medium-input technology and 14–19 GJ ha^{-1} in the low-input technology [44,108]. In the present experiment, energy consumption ranged from 14–19 GJ ha^{-1} (≤130 kg N ha^{-1}) to 22–27 GJ ha^{-1} (≥180 kg N ha^{-1}) regardless of cultivar. In western Asia (Turkey, Iraq), the energy inputs associated with rapeseed production were estimated at 18 GJ ha^{-1} [179,180]. In the Mediterranean Region (Italy, Greece, Croatia), energy consumption in the production of winter oilseed rape ranged from 9–10 GJ ha^{-1} to 17–23 GJ ha^{-1}, subject to the intensity of agricultural inputs [176,181,182]. In large-area farms in the northern USA, energy inputs in rapeseed production reached 9.5 GJ ha^{-1} [125].

The energy generation potential of biomass depends mainly on its energy efficiency ratio (ratio of energy outputs to energy inputs). In Europe, the energy efficiency ratio of rapeseed production ranges from 1.1–2.4 [176,177,183] to 3.5–5.4 [108,109,184]. In the present experiment, the most energy-efficient crop was the long-stem hybrid cultivar (Artoga), followed by the semi-dwarf cultivar (PR44 D06) and the open-pollinated cultivar (Adriana). The long-stem hybrid was characterized by the highest energy gain in the production technology with an N rate of 180 kg ha^{-1} and no S fertilization. This production technology is particularly recommended in small and medium-sized farms. In large-area farms where the availability of energy resources is the main limiting factor, the long-stem hybrid cultivar (Artoga) should be cultivated in a lower-input technology with an N rate of 80 kg ha^{-1} and no S fertilization (highest energy efficiency ratio). Sokólski et al. [120] also observed a relationship between cultivar and the energy efficiency of the production technology of winter oilseed rape. In their study, the optimal production technology of semi-dwarf cultivars was also most energy efficient. In turn, the cultivation of the long-stem cultivar of winter oilseed rape was most energy efficient in the low-input production technology [120].

5. Conclusions

The yield of the semi-dwarf morphotype of winter rapeseed was higher than that of the open-pollinated cultivar but lower than that of the long-stem hybrid cultivar. Nitrogen exerted a yield-forming effect up to a rate of 180 kg ha^{-1} in all studied cultivars. Higher N rates (230 kg ha^{-1}) improved yields only in years with low precipitation during the spring and summer growing seasons. Regardless of cultivar, the yield-forming effect of N rates higher than 180 kg ha^{-1} was apparent only in combination with an S rate of 40 kg S ha^{-1}. The ratio of seed yield to total biomass yield was higher in the semi-dwarf morphotype than in long-stem cultivars. The harvest index peaked in response to N rates of 130 kg ha^{-1} (long-stem hybrid) or 180 kg ha^{-1} (open-pollinated and semi-dwarf cultivars). The semi-dwarf hybrid cultivar accumulated significantly more crude fat and less total protein and GLS than long-stem cultivars. An increase in the N rate gradually decreased the crude fat content of winter oilseed rape seeds, in particular in long-stem cultivars. Nitrogen fertilization in spring increased the total protein content (to a greater extent in hybrid cultivars) and decreased the GLS content (to a greater extent in the semi-dwarf cultivar) of winter oilseed rape seeds. Sulfur fertilization increased the concentrations of total protein (in long-stem cultivars) and GLS (in all cultivars). Economic efficiency and energy efficiency were highest in the long-stem hybrid, followed by the semi-dwarf morphotype and the open-pollinated cultivar. The production of the long-stem hybrid cultivar generated the highest revenue in the technology involving 230 kg N ha^{-1} and 40 kg S ha^{-1} and the highest profit in the technology involving 130 kg N ha^{-1} and 40 kg S ha^{-1}. The energy efficiency of the long-stem hybrid cultivar peaked in response to the N rate of 180 kg ha^{-1} (highest energy gain per hectare) or 80 kg ha^{-1} (highest energy efficiency ratio) without sulfur fertilization.

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References

1. Faostat, Food and Agriculture Organization Corporate Statistical Database. Available online: http://www.apps.fao.org (accessed on 10 May 2020).
2. Hauska, D.; Oertel, C.; Alpmann, L.; Stelling, D.; Busch, H. Breeding progress towards high oil content in oilseed rape (*Brassica napus* L.)—Essential innovations to meet current and future market needs. In Proceedings of the 12th International Rapseed Congress, Wuhan, China, 26–30 March 2007; pp. 159–162.
3. Stefansson, B.R.; Hougen, F.W.; Downey, R.K. Note on the isolation of rape plants with seed oil free from erucic acid. *Can. J. Plant. Sci.* **1961**, *41*, 218–219. [CrossRef]
4. Krzymański, J. Variation in thioglucosides in rapeseed meal (*Brassica napus*). In Proceedings of the Meeting of the Associate Commitees of National Reseach Council on Plant Breeding, Winnipeg, MB, Canada, 20 February 1968.
5. Devouge, V.; Rogniaux, H.; Nesi, N.; Tessier, D.; Gueguen, J.; Larre, C. Differential proteomic analysis of four near-isogenic *Brassica napus* varieties bred for their erucic acid and glucosinolate contents. *J. Proteome Res.* **2007**, *6*, 1342–1353. [CrossRef]
6. Bocianowski, J.; Nowosad, K.; Liersch, A.; Popławska, W.; Łącka, A. Genotype-by-environment interaction for seed glucosinolate content in winter oilseed rape (*Brassica napus* L.) using an additive main effects and multiplicative interaction model. *Biom. Lett.* **2018**, *55*, 85–96. [CrossRef]

7. Pruvot, J.; Kraling, K.; Charne, D.; Tulsieram, L. Development of low glucosinolate restorer and OGU CMS winter rape hybrid. In Proceedings of the 10th International Rapeseed Congress, Canberra, Australia, 26–29 September 1999; pp. 270–273.
8. Rathke, G.W.; Behrens, T.; Diepenbrock, W. Integrated nitrogen management strategies to improve seed yield, oil content and nitrogen efficiency of winter oilseed rape (*Brassica napus* L.): A review. *Agric. Ecosyst. Environ.* **2006**, *117*, 80–108. [CrossRef]
9. Broniarz, J.; Paczocha, J. *Preliminary Yield Values in Experiments Conducted After Cultivar Registration*; COBORU: Słupia Wielka, Poland, 2019; pp. 1–9. (In Polish)
10. 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]
11. Siger, A.; Michalak, M.; Cegielska-Taras, T.; Szała, L.; Lembicz, J.; Nogala-Kałucka, M. Genotype and environment effects on tocopherol and plastochromano l-8 contents of winter oilseed rape doubled haploid lines derived from F1 plants of the cross between yellow and black seeds. *Ind. Crops Prod.* **2015**, *65*, 134–141. [CrossRef]
12. Gan, Y.; Malhi, S.S.; Brandt, S.A.; McDonald, C.L. Assessment of seed shattering resistance and yield loss in five oilseed crops. *Can. J. Plant. Sci.* **2008**, *88*, 267–270. [CrossRef]
13. Abedi, T.; Pakniyat, H. Antioxidant enzymes changes in response to drought stress in ten cultivars of oilseed rape (*Brassica napus* L.). *Czech. J. Genet. Plant. Breed.* **2010**, *46*, 27–34. [CrossRef]
14. Faraji, A.; Latifi, N.; Soltani, A.; Rad, A.H.S. Seed yield and water use efficiency of canola (*Brassica napus* L.) as affected by high temperature stress and supplemental irrigation. *Agric. Water Manag.* **2009**, *96*, 132–140. [CrossRef]
15. Waalen, W.M.; Tanino, K.K.; Olsen, J.E.; Eltun, R.; Rognli, O.A.; Gusta, L.V. Freezing tolerance of winter canola cultivars is best revealed by a prolonged freeze test. *Crop. Sci.* **2011**, *51*, 1988–1996. [CrossRef]
16. Pace, R.; Benincasa, P. Effect of salinity and low osmotic potential on the germination and seedling growth of rapeseed cultivars with different stress tolerance. *Ital. J. Agron.* **2010**, *5*, 69–78. [CrossRef]
17. Khan, S.; Anwar, S.; Kuai, J.; Noman, A.; Shahid, M.; Din, M.; Ali, A.; Zhou, G. Alteration in yield and oil quality traits of winter rapeseed by lodging at different planting density and nitrogen rates. *Sci. Rep.* **2018**, *8*, 634. [CrossRef] [PubMed]
18. Brazauskiene, I.; Petraitiene, E.; Brazauskas, G.; Ronis, A. Susceptibility of winter rape cultivars to fungal diseases and their response to fungicide application. *Turk. J. Agric. For.* **2013**, *37*, 699–710. [CrossRef]
19. Hervé, M.R. Breeding for insect resistance in oilseed rape: Challenges, current knowledge and perspectives. *Plant. Breed.* **2018**, *137*, 27–34. [CrossRef]
20. Slominski, B.A.; Jia, W.; Mikulski, D.; Rogiewicz, A.; Jankowski, J.; Rakow, G.; Jones, R.O.; Hickling, D. Chemical composition and nutritive value of low-fiber yellow-seeded *B. napus* and *B. juncea* canola for poultry. In Proceedings of the 13th International Rapeseed Congress, Prague, Czech Republic, 5–9 June 2011; pp. 443–445.
21. Chiriac, G.; Lucian, R.A.; Coroi, I.G.; Gales, D.C.; Jitareanu, G. Effect of tillage and cultivar on winter oilseed rape (*Brassica napus* L.) yield and economic efficiency in Suceava Plateau. *ProEnviron./Promediu* **2013**, *6*, 130–135.
22. Krček, V.; Baranyk, P.; Pulkrabek, J.; Urban, J.; Skerikova, M.; Brant, V.; Zabransky, Z. Influence of crop management on winter oilseed rape yield formation—Evaluation of first year of experiment. *Mendelnet* **2014**, *2*, 57–63.
23. Miersch, S.; Gertz, A.; Breuer, F.; Schierholt, A.; Becker, H.C. Influence of the semi-dwarf growth type on seed yield and agronomic parameters at low and high nitrogen fertilization in winter oilseed rape. *Crop. Sci.* **2016**, *56*, 1573–1585. [CrossRef]
24. Pinochet, X.; Renard, M. Rapeseed genetic progress and outlook for developments. OCL: Oilseeds and fats. *Crops Lipids* **2012**, *19*, 147–154. (In French)
25. Grzebisz, W. Microelements in plant nutrition. In *Crop Fertilization*; Grzebisz, W., Ed.; PWRiL: Poznań, Poland, 2008; Volume 1, pp. 261–292. (In Polish)
26. Litke, L.; Gaile, Z.; Ruža, A. Effect of nitrogen rate on nitrogen use efficiency in winter oilseed rape (*Brassica napus*). *Res. Rural. Dev.* **2019**, *2*, 43–49.

27. Liao, J.; Liu, X.; Hu, A.; Song, H.; Chen, X.; Zhang, Z. Effects of biochar-based controlled release nitrogen fertilizer on nitrogen-use efficiency of oilseed rape (*Brassica napus* L.). *Sci. Rep.* **2020**, *10*, 1–14. [CrossRef]
28. Wang, L.; Lu, P.; Ren, T.; Liu, T.; Geilfus, C.M.; Lu, J. Improved nitrogen efficiency in winter oilseed rape hybrid compared with the parental lines under contrasting nitrogen supply. *Ind. Crops Prod.* **2020**, *155*, 112777. [CrossRef]
29. Sylvester-Bradley, R.; Kindred, D.R. Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. *J. Exp. Bot.* **2009**, *60*, 1939–1951. [CrossRef] [PubMed]
30. Kessel, B.; Schierholt, A.; Becker, H.C. Nitrogen use efficiency in a genetically diverse set of winter oilseed rape (*Brassica napus* L.). *Crop. Sci.* **2012**, *52*, 2546–2554. [CrossRef]
31. Haneklaus, S.; Paulsen, H.M.; Gupta, A.K.; Bloem, E.; Schnug, E. Influence of sulfur fertilization on yield and quality of oilseed rape and mustard. In Proceedings of the 10th International Rapeseed Congress, Canberra, Australia, 26–29 September 1999; Volume 1, pp. 26–29.
32. Scherer, H.W. Sulphur in crop production—Invited paper. *Eur. J. Agron.* **2001**, *14*, 81–111. [CrossRef]
33. Tisdale, S.L.; Reneau, R.B.; Patou, J.S. Atlas of sulfur deficiencies. In *Sulfur in Agriculture*; Tabatabai, M.A., Ed.; Agronomy no. 27; American Society of Agronomy: Madison, WI, USA, 1986; pp. 295–322.
34. Jankowski, K.J.; Budzyński, W.S.; Kijewski, Ł.; Zając, T. Biomass quality of *Brassica* oilseed crops in response to sulfur fertilization. *Agron. J.* **2015**, *107*, 1377–1391. [CrossRef]
35. Haneklaus, S.; Bloem, E.; Schnug, E. History of sulfur deficiency in crops. In *Sulfur: A Missing Link between Soils. Crops, and Nutrition*, 1st ed.; Jez, J., Ed.; Soil Science Society of America: Madison, WI, USA, 2008; pp. 45–58.
36. Withers, P.J.A.; Evans, E.J.; Bilsborrow, P.E.; Milord, G.F.J.; McGrath, S.P.; Zhao, F.; Walter, K.C. Improving the prediction of sulphur deficiency in winter oilseed rape in the UK. In Proceedings of the 9th International Rapeseed Congress, Cambridge, UK, 4–7 July 1995; Volume 1, pp. 277–279.
37. Bilsborrow, P.E.; Evans, E.J.; Milford, G.F.J.; Fieldsend, M.J. The effects of S and N on the yield and quality of oilseed rape in the U.K. In Proceedings of the 9th International Rapeseed Congress, Cambridge, UK, 4–7 July 1995; Volume 1, pp. 280–283.
38. Šiaudinis, G.; Butkutė, B. Responses of spring oilseed rape seed yield and quality to nitrogen and sulfur fertilization. *Commun. Soil Sci. Plant. Anal.* **2013**, *44*, 145–157. [CrossRef]
39. Schnug, E. Physiological functions and enviromental relevance of sulfur-containing secondary metabolites. In *Sulfur Nutrition and Assimilation in Higher Plants; Regulatory Agricultural and Environmental Aspects*; De Kok, L.J., Stulen, I., Rennenberg, H., Brunold, C., Rauser, W.E., Eds.; SPB Academic Publishing: Hague, The Netherlands, 1993; pp. 179–190.
40. De Kok, L.J.; Castro, A.; Durenkamp, M.; Stuiver, C.E.E.; Westerman, S.; Yang, L.; Stulen, I. Sulphur in plant physiology. *Fertil. Fertil.* **2003**, *5*, 55–80.
41. 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. Nutr.* **2010**, *33*, 1216–1228. [CrossRef]
42. Ma, B.L.; Zheng, Z.; Whalen, J.K.; Caldwell, C.; Vanasse, A.; Pageau, D.; Scott, P.; Earl, H.; Smith, D.L. Uptake and nutrient balance of nitrogen, sulfur, and boron for optimal canola production in eastern Canada. *J. Plant. Nutr. Soil Sci.* **2019**, *182*, 252–264. [CrossRef]
43. McGrath, S.P.; Zhao, F.J. Sulphur uptake, yield responses and the interactions between nitrogen and sulphur in winter oilseed rape (*Brassica napus*). *J. Agr. Sci.* **1996**, *126*, 53–62. [CrossRef]
44. Jankowski, K.J. The influence of environmental and agronomic factors on the production of winter rapeseed for food processing and energy generation. In *Monographs and Scientific Dissertations*; UWM: Olsztyn, Poland, 2007; pp. 1–174. (In Polish)
45. Ahmad, G.; Jan, A.; Arif, M.; Jan, M.T.; Shah, H. Effect of nitrogen and sulfur fertilization on yield components, seed and oil yields of canola. *J. Plant. Nutr.* **2011**, *34*, 2069–2082. [CrossRef]
46. Lucas, F.T.; Coutinho, E.L.M.; Paes, J.M.V.; Barbosa, J.C. Yield and quality of canola grains due to nitrogen and sulfur fertilization. *Semin Cienc Agrar.* **2013**, *34*, 3205–3218. [CrossRef]
47. Filipek-Mazur, B.; Tabak, M.; Gorczyca, O.; Lisowska, A. Effect of sulfur-containing fertilizers on the quantity and quality of spring oilseed rape and winter wheat yield. *J. Elem.* **2019**, *24*, 1383–1394.
48. Jiang, Y.; Caldwell, C.D.; Falk, K.C.; Lada, R.R.; MacDonald, D. *Camelina* yield and quality response to combined nitrogen and sulfur. *Agron. J.* **2013**, *105*, 1847–1852. [CrossRef]

49. Wysocki, D.J.; Chastain, T.G.; Schillinger, W.F.; Guy, S.O.; Karow, R.S. *Camelina*: Seed yield response to applied nitrogen and sulfur. *Field Crops Res.* **2013**, *145*, 60–66. [CrossRef]
50. Jankowski, K.J.; Sokólski, M.; Kordan, B. Camelina: Yield and quality response to nitrogen and sulfur fertilization in Poland. *Ind. Crops Prod.* **2019**, *141*, 111776. [CrossRef]
51. Ahmad, A.; Abraham, G.; Gandotra, N.; Abrol, Y.P.; Abdin, M.Z. Interactive effect of nitrogen and sulphur on growth and yield of rape-seed-mustard (*Brassica juncea* L. Czern. and Coss. and *Brassica campestris* L.) genotypes. *J. Agron. Crop Sci.* **1998**, *181*, 193–199. [CrossRef]
52. Kumar, S.; Verma, S.K.; Singh, T.K.; Shyambeer, S. Effect of nitrogen and sulphur on growth, yield and nutrient uptake by Indian mustard (*Brassica juncea*) under rainfed condition. *Indian J. Agric. Sci.* **2011**, *81*, 145–149.
53. Kovács, A.B.; Kincses, I.; Vágó, I.; Loch, J.; Filep, T. Effect of application of nitrogen and different nitrogen-sulfur ratios on the quality and quantity of mustard seed. *Commun. Soil Sci. Plan.* **2009**, *40*, 453–461. [CrossRef]
54. Jankowski, K.J.; Załuski, D.; Sokólski, M. Canola-quality white mustard: Agronomic management and seed yield. *Ind. Crops Prod.* **2020**, *145*, 112138. [CrossRef]
55. Fismes, J.; Vong, P.C.; Guckert, A.; Frossard, E. Influence of sulfur on apparent N-use efficiency, yield and quality of oilseed rape (*Brassica napus* L.) grown on a calcareous soil. *Eur. J. Agron.* **2000**, *12*, 127–141. [CrossRef]
56. Egesel, C.Ö.; Gül, M.K.; Kahrıman, F. Changes in yield and seed quality traits in rapeseed genotypes by sulphur fertilization. *Eur. Food Res. Technol.* **2009**, *229*, 505–513. [CrossRef]
57. 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]
58. Verkerk, R.; Schreiner, M.; Krumbein, A.; Ciska, E.; Holst, B.; Rowland, I.; De Schrijver, R.; Hansen, M.; Gerhauser, C.; Mithen, R.; et al. Glucosinolates in *Brassica* vegetables: The influence of the food supply chain on intake, bioavailability and human health. *Mol. Nutr. Food Res.* **2009**, *53*, 219–265. [CrossRef]
59. Binkowski, M.; Broniarz, J.; Janiak, W.; Lenartowicz, T.; Osiecka, A.; Paczocha, J.; Piecuch, K.; Stuczyńska, E. *Descriptive List of Agricultural Cultivars–Beetroots, Potatoes, Oilseed Crops, Forage Crops*; COBORU: Słupia Wielka, Poland, 2019; pp. 1–172. (In Polish)
60. Moreno, D.A.; Carvajal, M.; López-Berenguer, C.; García-Viguera, C. Chemical and biological characterisation of nutraceutical compounds of broccoli. *J. Pharm. Biomed. Anal.* **2006**, *41*, 1508–1522. [CrossRef]
61. Narits, L. Effect of nitrogen rate and application time to yield and quality of winter oilseed rape (*Brassica napus* L. var. *oleifera* subvar. *biennis*). *Agron. Res.* **2010**, *8*, 671–686.
62. Lošák, T.; Hlušek, J.; Martinec, J.; Vollmann, J.; Peterka, J.; Filipčík, R.; Varga, L.; Ducsay, L.; Martensson, A. Effect of combined nitrogen and sulphur fertilization on yield and qualitative parameters of *Camelina sativa* [L.] Crtz. (false flax). *Acta Agric. Scand. Section B Soil Plant. Sci.* **2011**, *4*, 313–321.
63. Czarnik, M.; Jarecki, W.; Bobrecka-Jamro, D. The effects of varied plant density and nitrogen fertilization on quantity and quality yield of *Camelina sativa* L. *Emir. J. Food Agric.* **2017**, *29*, 988–993.
64. Poisson, E.; Trouverie, J.; Brunel-Muguet, S.; Akmouche, Y.; Pontet, C.; Pinochet, X.; Avice, 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*, 1–14. [CrossRef]
65. Öztürk, Ö. Effects of source and rate of nitrogen fertilizer on yield, yield components and quality of winter rapeseed (*Brassica napus* L.). *Chil. J. Agr. Res.* **2010**, *70*, 132–141. [CrossRef]
66. Cheema, M.A.; Saleem, M.F.; Muhammad, N.; Wahid, M.A.; Baber, B.H. Impact of rate and timing of nitrogen application on yield and quality of canola (*Brassica napus* L.). *Pak. J. Bot.* **2010**, *42*, 1723–1731.
67. White, C.A.; Roques, S.E.; Berry, P.M. Effects of foliar-applied nitrogen fertilizer on oilseed rape (*Brassica napus*). *J. Agr. Sci.* **2015**, *153*, 42–55. [CrossRef]
68. Joshi, N.L.; Mali, P.C.; Saxena, A. Effect of nitrogen and sulphur application on yield and fatty acid composition of mustard (*Brassica juncea* L.) oil. *J. Agron. Crop. Sci.* **1998**, *180*, 59–63. [CrossRef]
69. Brennan, R.F.; Mason, M.G.; Walton, G.H. Effect of nitrogen fertilizer on the concentrations of oil and protein in canola (*Brassica napus*) seed. *J. Plant. Nutr.* **2000**, *23*, 339–348. [CrossRef]
70. Bilsborrow, P.E.; Evans, E.J.; Zhao, F.J. The influence of spring nitrogen on yield, yield components and glucosinolate content of autumn-sown oilseed rape (*Brassica napus*). *J. Agr. Sci.* **1993**, *120*, 219–224. [CrossRef]
71. Thakral, S.K.; Singh, B.P.; Faroda, A.S.; Gupta, S.K. Effect of irrigation and fertility levels on the oil yield and quality of *Brassica* species. *Ann. Agric. Res.* **1996**, *17*, 416–418.

72. Chen, X.J.; Zhu, Z.J.; Ni, X.L.; Qian, Q.Q. Effect of nitrogen and sulfur supply on glucosinolates in *Brassica campestris* ssp. *chiensis*. *Agric. Sci. China* **2006**, *5*, 603–608. [CrossRef]
73. Omirou, M.D.; Papadopoulou, K.K.; Papastylianou, I.; Constantinou, M.; Karpouzas, D.G.; Asimakopoulos, I.; Ehaliotis, C. Impact on nitrogen and sulfur fertilization on the composition of glucosinolates in relation to sulfur assimilation in different plant organs of broccoli. *J. Agric. Food Chem.* **2009**, *57*, 9408–9417. [CrossRef]
74. Zhao, F.; Evans, E.J.; Bilsborrow, P.E.; Syers, J.K. Influence of nitrogen and sulphur on the glucosinolate profile of rapeseed (*Brassica napus*). *J. Sci. Food Agric.* **1994**, *64*, 295–304. [CrossRef]
75. Grant, C.A.; Malhi, S.S.; Karamanos, R.E. Sulfur management for rapeseed. *Field Crops Res.* **2012**, *128*, 119–128. [CrossRef]
76. Jankowski, K.J.; Kijewski, Ł.; Groth, D.; Skwierawska, M.; Budzyński, W.S. The effect of sulfur fertilization on macronutrient concentrations in the post-harvest biomass of rapeseed (*Brassica napus* L. ssp. *oleifera* Metzg). *J. Elem.* **2015**, *20*, 585–597. [CrossRef]
77. Jankowski, K.J.; Krzebietke, S.; Budzyński, W.S. The effect of sulphur fertilization on macronutrient concentrations in the post-harvest biomass of mustard. *Plant. Soil Environ.* **2015**, *61*, 266–272.
78. Chahal, H.S.; Sing, A.; Malhi, G.S. Role of Sulphur nutrition in oilseed crop production—A review. *J. Oilseeds Res.* **2020**, *11*, 95–102.
79. Szulc, P.M.; Drozdowska, L.; Kachlicki, P. Effect of sulphur on the yield and content of glucosinolates in spring oilseed rape seeds. *EJPAU* **2003**, *6*, 1–8.
80. Ahmad, G.; Jan, A.; Arif, M.; Jan, M.T.; Khattak, R.A. Influence of nitrogen and sulfur fertilization on quality of canola (*Brassica napus* L.) under rainfed conditions. *J. Zhejiang Univ. Sci. B* **2007**, *8*, 731–737. [CrossRef]
81. Bahmanyar, M.; Poshtmasari, H.K. Influence of nitrogen and sulfur on yield and seed quality of three canola cultivars. *J. Plant. Nutr.* **2010**, *33*, 953–965. [CrossRef]
82. 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**, *61*, 164–170. [CrossRef]
83. Jankowski, K.J.; Budzyński, W.S.; Szymanowski, A. Effect of sulfur on the quality of winter rape seeds. *J. Elem.* **2008**, *13*, 521–534.
84. Ahmad, A.; Abdin, M.Z. Effect of sulphur application on lipid, RNA and fatty acid content in developing seeds of rapeseed (*Brassica campestris* L.). *Plant. Science* **2000**, *150*, 71–76. [CrossRef]
85. Gaj, R.; Klikocka, H. Multifunctional sulphur effect in plants—From nutrition to protection. *Prog. Plant. Prot.* **2011**, *1*, 33–44. (In Polish)
86. Hell, R.; Rennenberg, H. The plant sulphur cycle. In *Sulphur in Agroecosystems, Part of the Series, Vol. 2: Nutrient in Ecosystems*; Schnug, E., Ed.; Kluwer Academic Publishers: Dordrecth, The Netherlands, 1998; pp. 135–174.
87. Zhao, F.J.; Withers, P.J.A.; Evans, E.J.; Monaghan, J.; Salmon, S.E.; Shewry, P.R.; McGrath, S.P. Sulphur nutrition: An important factor for the quality of wheat and rapeseed. *Soil Sci. Plant. Nutr.* **1997**, *43*, 1137–1142. [CrossRef]
88. Malhi, S.S.; Gill, K.S. Effectiveness of sulphate-S fertilization at different growth stages for yield, seed quality and S uptake of canola. *Can. J. Plant. Sci.* **2002**, *82*, 665–674. [CrossRef]
89. Nowak-Polakowska, H.; Czaplicki, S.; Tańska, M.; Jankowski, K.J. Chemical composition of white and sarepta mustard seeds as affected by differentiated conditions of nitrogen top-dressing at sowing-preceding fertilization with sulphur and magnesium. *Pol. J. Nat. Sci.* **2005**, *18*, 25–39.
90. Hassan, F.U.; Manaf, A.; Quadir, G.; Basra, S.M.A. Effects of sulphur on seed yield, oil, protein and glucosinolates of canola cultivars. *Int. J. Agri. Biol.* **2007**, *9*, 504–508.
91. Šiaudinis, G. The effect of nitrogen and sulphur fertilisation on the elemental composition and seed quality of spring oilseed rape. *Žemdirbystė (Agriculture)* **2010**, *97*, 47–56.
92. Gerendás, J.; Podestát, J.; Stahl, T.; Kübler, K.; Brückner, H.; Mersch-Sundermann, V.; Mühling, K.H. Interactive effects of sulfur and nitrogen supply on the concentration of sinigrin and allyl isothiocyanate in Indian mustard (*Brassica juncea* L.). *J. Agric. Food Chem.* **2009**, *57*, 3837–3844. [CrossRef]
93. Rehman, H.; Iqbal, Q.; Farooq, M.; Wahid, A.; Afzal, I.; Basra, S.M. Sulphur application improves the growth, seed yield and oil quality of canola. *Acta Physiol. Plant.* **2013**, *35*, 2999–3006. [CrossRef]
94. Gugała, M.; Sikorska, A.; Zarzecka, K. The effect of fertilization with sulphur, boron, and amino acids on the content of glucosinolate in winter rape seeds. *Agronomy* **2020**, *10*, 519. [CrossRef]

95. Wielebski, F. Sulphur fertilization of different types of winter oilseed rape varieties in various soil conditions. II. Effect on quality and chemical composition of seeds. *Rośliny Oleiste: Oilseed Crops* **2006**, *27*, 283–298. (In Polish)
96. Wielebski, F. The effect of sulphur fertilization on the yield of different breeding forms of winter oilseed rape in the conditions of diverse nitrogen rates. *Rośliny Oleiste: Oilseed Crops* **2011**, *32*, 61–78. (In Polish)
97. Merrien, A.; Ribaillier, D.; Agbo, P.; Davineau, J. Impact de la fertilisation soufre sur la teneur en glucosinolates des greins chez le colza: Consequences agronomiques. In Proceedings of the 7th International Congress Sur le Colza, Poznań, Poland, 10–14 May 1987; pp. 907–916. (In French).
98. Dobele, A.; Pilvere, I.; Ruza, L.; Grigorjeva, R. Economic evaluation of rape production on the member farms of the cooperative LATRAPS. *Econ. Sci. Rural Dev.* **2011**, *24*, 21–29.
99. Homolka, J.; Bubeníková, V. Economic evaluation of intensive growing of selected crops. *Agris On-Line Pap. Econ. Inf.* **2013**, *5*, 47–58.
100. Dobek, T.K.; Sałagan, P. Influence of the production costs of winter rape seeds on the value of the produced biodiesel. *Inż. Rol.* **2011**, *15*, 21–28. (In Polish)
101. Dobek, T.K.; Rynkiewicz, M.; Červinka, J.; Mareček, J. Energy and economic effectiveness of winter rape and winter wheat cultivation for liquid biofuel production. *Acta Univ. Agric. Silivic. Mendel. Brun.* **2013**, *61*, 1255–1259. [CrossRef]
102. Jabłoński, K.; Skarżyńska, A.; Abramczuk, Ł. Determinants of income from wheat and rape production in projection for 2020 in Poland. *Žemės Ūkio Mokslai* **2015**, *22*, 229–239. [CrossRef]
103. Skarżyńska, A. Technical, economic and environmental efficiency of production of selected plant products in the agricultural Polish regions. *Probl. Agric. Econ.* **2017**, *1*, 117–137.
104. Nilsson, C.; Buechs, W.; Klukowski, Z.; Luik, A.; Ulber, B.; Williams, I.H. Integrated crop and pest management of winter oilseed rape (*Brassica napus* L.). *Žemdirbystė (Agriculture)* **2015**, *102*, 325–334. [CrossRef]
105. Skarżyńska, A. Cropping intensity vs. profitability of selected plant production activities in Poland. *Stud. Agric. Econ.* **2012**, *114*, 31–38. [CrossRef]
106. Wenda-Piesik, A.; Hoppe, S. Evaluation of hybrid and population cultivars on standard and high-input technology in winter oilseed rape. *Acta Agric. Scand.* **2018**, *68*, 678–689.
107. Yue, D.; You, F.; Snyder, S.W. Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. *Comput. Chem. Eng.* **2014**, *66*, 36–56. [CrossRef]
108. Budzyński, W.S.; Jankowski, K.J.; Jarocki, M. An analysis of the energy efficiency of winter rapeseed biomass under different farming technologies. A case study of a large-scale farm in Poland. *Energy* **2015**, *90*, 1272–1279. [CrossRef]
109. Jankowski, K.J.; Budzyński, W.S.; Kijewski, Ł. An analysis of energy efficiency in the production of oilseed crops of the family *Brassicaceae* in Poland. *Energy* **2015**, *81*, 674–681. [CrossRef]
110. Jankowski, K.J.; Dubis, B.; Budzyński, W.S.; Bórawski, P.; Bułkowska, K. Energy efficiency of crops grown for biogas production in a large-scale farm in Poland. *Energy* **2016**, *109*, 277–286. [CrossRef]
111. Stolarski, M.J.; Krzyżaniak, M.; Kwiatkowski, J.; Tworkowski, J.; Szczukowski, S. Energy and economic efficiency of camelina and crambe biomass production on a large-scale farm in north-eastern Poland. *Energy* **2018**, *150*, 770–780. [CrossRef]
112. Bielski, S.; Romaneckas, K.; Novikova, A.; Šarauskis, E. Are higher input levels to triticale growing technologies effective in biofuel production system? *Sustainability* **2019**, *11*, 5915. [CrossRef]
113. Bórawski, P.; Bełdycka-Bórawska, A.; Szymańska, E.J.; Jankowski, K.J.; Dubis, B.; Dunn, J.W. Development of renewable energy sources market and biofuels in the European Union. *J. Clean. Prod.* **2019**, *228*, 467–484. [CrossRef]
114. Dubis, B.; Jankowski, K.J.; Załuski, D.; Bórawski, P.; Szempliński, W. Biomass production and energy balance of Miscanthus over a period of 11 years: A case study in a large-scale farm in Poland. *GCB Bioenergy* **2019**, *11*, 1187–1201. [CrossRef]
115. Stolarski, M.J.; Krzyżaniak, M.; Tworkowski, J.; Załuski, D.; Kwiatkowski, J.; Szczukowski, S. Camelina and crambe production—Energy efficiency indices depending on nitrogen fertilizer application. *Ind. Crops Prod.* **2019**, *137*, 386–395. [CrossRef]
116. Zegada-Lizarazu, W.; Elbersen, H.W.; Cosentino, S.L.; Zatta, A.; Alexopoulou, E.; Monti, A. Agronomic aspects of future energy crops in Europe. *Biofuels Bioprod. Bioref.* **2010**, *4*, 674–691. [CrossRef]

117. Kusek, G.; Ozturk, H.H.; Akdemir, S. An assessment of energy use of different cultivation methods for sustainable rapeseed production. *J. Clean. Prod.* **2016**, *112*, 2772–2783. [CrossRef]
118. Meier, U. Growth stages of mono- and dicotyledonous plants. In *BBCH Monograph*; Julius Kühn-Institut: Quedlinburg, Germany, 2018; Available online: https://www.julius-kuehn.de/media/Veroeffentlichungen/bbch%20epaper%20en/page.pdf (accessed on 28 May 2020).
119. IUSS Working Group WRB. *World Reference Base for Soil Resources*, 2nd ed.; World Soil Resources Reports No. 103; FAO: Rome, Italy, 2006; p. 132.
120. Sokólski, M.; Jankowski, K.J.; Załuski, D.; Szatkowski, A. Productivity, energy and economic balance in the production of different cultivars of winter oilseed rape. A case study in north-eastern Poland. *Agronomy* **2020**, *10*, 508. [CrossRef]
121. Panak, H. *Agricultural Chemistry*; ART: Olsztyn, Poland, 1997; 258p. (In Polish)
122. Jankowski, K.J.; Sokólski, M.; Dubis, B.; Krzebietke, S.; Żarczyński, P.; Hulanicki, P.; Hulanicki, P.S. Yield and quality of winter oilseed rape (*Brassica napus* L.) seeds in response to foliar application of boron. *Agr. Food Sci.* **2016**, *25*, 164–176. [CrossRef]
123. Pawlak, J. *Organizational and Economic Aspects of Automated Plant Production Systems in Family Farms*; PWRiL: Warszawa, Poland, 1989. (In Polish)
124. Wójcicki, Z. *Equipment, Materials and Energy Inputs in Growth-Oriented Farms*; IBMER: Warszawa, Poland, 2000. (In Polish)
125. Fore, S.R.; Porter, P.; Lazarus, W. Net energy balance of small-scale on-farm biodiesel production from canola and soybean. *Biomass Bioenerg.* **2011**, *35*, 2234–2244. [CrossRef]
126. *Statistica, Version 10.0*, Data Analysis Software System; Statsoft Inc.: Tulsa, OK, USA, 2010.
127. Korbas, M.; Jajor, E.; Budka, A. Clubroot (*Plasmodiophora brassicae*)—A threat for oilseed rape. *J. Plant. Prot. Res.* **2009**, *49*, 446–451. [CrossRef]
128. Huang, S.; Gruber, S.; Claupein, W. Field history of imidazolinone-tolerant oilseed rape (*Brassica napus*) volunteers in following crops under six long-term tillage systems. *Field Crops Res.* **2016**, *185*, 51–58. [CrossRef]
129. Ratajczak, K.; Sulewska, H.; Szymańska, G. New winter oilseed rape varieties—seed quality and morphological traits depending on sowing date and rate. *Plant. Prod. Sci.* **2017**, *20*, 262–272. [CrossRef]
130. Clarke, S.M.; Berry, P.M.; Roques, S.; Draye, X.; Foulkes, J.; Hawkesford, M. A comparison of semi-dwarf and standard height oilseed rape varieties on N use efficiency and its components. *Aspects Appl. Biol.* **2010**, *105*, 115–123.
131. Wielebski, F.; Wójtowicz, M. Effect of date and density of sowing and weather conditions on seed yield and yield components of winter oilseed rape morfotypes with traditional and semi-draft type of growth. *Fragm. Agron.* **2018**, *35*, 133–145. (In Polish)
132. Sieling, K.; Kage, H. The potential of semi-dwarf oilseed rape genotypes to reduce the risk of N leaching. *J. Agric. Sci.* **2008**, *146*, 77–84. [CrossRef]
133. Gugała, M.; Sikorska, A.; Findura, P.; Kapela, K.; Malaga-Tobola, U.; Zarzecka, K.; Domanski, L. Effect of selected plant preparations containing biologically active compounds on winter rape (*Brassica napus* L.) yielding. *Appl. Ecol. Environ. Res.* **2019**, *17*, 2779–2789. [CrossRef]
134. Wielebski, F. Response of different types of winter oilseed rape varieties to sowing date and to various plant density in the field. *Prosperující olejniny* **2014**, 48–52, (In Czech with English abstract).
135. Dresbøll, D.B.; Rasmussen, I.S.; Thorup-Kristensen, K. The significance of litter loss and root growth on nitrogen efficiency in normal and semi-dwarf winter oilseed rape genotypes. *Field Crops Res.* **2016**, *186*, 166–178. [CrossRef]
136. Schuster, C.; Rathke, G.W. Nitrogen fertilisation of transgenic winter oilseed rape. In *Plant Nutrition: Food Security and Sustainability of Agro-Ecosystems through Basic and Applied Research*; Horst, W.J., Schenk, M.K., Bürkert, A., Claassen, N., Flessa, H., Frommer, W.B., Goldbach, H., Olfs, H.-W., Römheld, V., Sattelmacher, B., et al., Eds.; Kluwer Academic Publishers: Berlin, Germany, 2001; pp. 798–799.
137. Barłóg, P.; Grzebisz, W. Effect of timing and nitrogen fertilizer application on winter oilseed rape (*Brassica napus* L.). II. Nitrogen uptake dynamics and fertilizer efficiency. *J. Agron. Crop. Sci.* **2004**, *190*, 314–323. [CrossRef]
138. Boelcke, B.; Léon, J.; Schulz, R.R.; Schröder, G.; Diepenbrock, W. Yield stability of winter oil-seed rape (*Brassica napus* L.) as affected by stand establishment and nitrogen fertilization. *J. Agron. Crop. Sci.* **1991**, *167*, 241–248. [CrossRef]

139. Zhao, F.; Evans, E.J.; Bilsborrow, P.E.; Syers, J.K. Influence of sulphur and nitrogen on seed yield and quality of low glucosinolate oilseed rape (*Brassica napus* L.). *J. Sci. Food Agric.* **1993**, *63*, 29–37. [CrossRef]
140. Yusuf, R.I.; Bullock, D.G. Effect of several production factors on two varieties of rapeseed in the central United States. *J. Plant. Nutr.* **1993**, *16*, 1279–1288. [CrossRef]
141. Wojnowska, T.; Panak, H.; Sienkiewicz, S. The responses of winter rapeseed to increasing rates of nitrogen fertilization on black soils in Kętrzyn. *Rośliny Oleiste–Oilseed Crops* **1995**, *1*, 173–180. (In Polish)
142. Shepherd, M.A.; Sylvester-Bradley, R. Effect of nitrogen fertilizer applied to winter oilseed rape (*Brassica napus*) on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen fertilizer. *J. Agr. Sci.* **1996**, *126*, 63–74. [CrossRef]
143. Barszczak, Z.; Barszczak, T.; Górczyński, J. The influence of periodic drought and soil salinity on the yield of winter rapeseed supplied with different rates of N fertilizer. *Post. Nauk Roln.* **1993**, *6*, 15–23. (In Polish)
144. Kessel, B.; Becker, H.C. Genetic variation of nitrogen-efficiency in field experiments with oilseed rape (*Brassica napus* L.). In *Plant Nutrition–Molecular Biology and Genetics*; Gissel-Nielsen, G., Jensen, A., Eds.; Springer: Dodrecht, The Netherlands, 1999; pp. 391–395.
145. Wójtowicz, M. The influence of environmental and agronomic factors on seed yield and yield quality of winter rapeseed (*Brassica napus* L.). *Monogr. Sci. Diss.* **2013**, *45*, 1–111. (In Polish)
146. Frick, J.; Nielsen, S.S.; Mitchell, C.A. Yield and seed oil content response of dwarf, rapid-cycling *Brassica* to nitrogen treatments, planting density, and carbon dioxide enrichment. *J. Am. Soc. Hortic. Sci.* **1994**, *119*, 1137–1143. [CrossRef] [PubMed]
147. Cheema, M.A.; Saleem, M.; Malik, M.A.A. Effect of row spacing and nitrogen management of agronomic traits and oil quality of canola (*Brassica napus* L.). *Pak. J. Agric. Sci.* **2001**, *38*, 15–18.
148. Schnug, E.; Haneklaus, S. Sulphur deficiency in oilseed rape flowers–symptomatology, biochemistry and ecological impacts. In Proceedings of the 9th International Rapeseed Congress, Cambridge, UK, 4–7 July 1995; Volume 1, pp. 296–298.
149. Zhao, F.J.; Wood, A.P.; McGrath, S.P. Effects of sulphur nutrition on growth and nitrogen fixation of pea (*Pisum sativum* L.). *Plant. Soil* **1999**, *212*, 207–217. [CrossRef]
150. Budzyński, W.S.; Ojczyk, T. Influence of sulphur fertilization on seed yield and seed quality of double low oilseed rape. In Proceedings of the 9th International Rapeseed Congress, Cambridge, UK, 4–7 July 1995; Volume 1, pp. 284–286.
151. Malhi, S.S.; Gan, Y.; Raney, J.P. Yield, seed quality, and sulfur uptake of *Brassica* oilseed crops in response to sulfur fertilization. *Agron. J.* **2007**, *99*, 570–577. [CrossRef]
152. Zukalová, H.; Matula, J.; Vasak, J. Effect of sulphur fertilization upon biomass dry matter production dynamics and glucosinolate biosynthesis in three types of winter oilseed rape (*Brassica napus* L.). *Rośliny Oleiste–Oilseed Crops* **2001**, *22*, 273–284. (In Polish)
153. Wielebski, F.; Wójtowicz, M. Effect of spring sulphur fertilization on yield and glucosinolate content in seeds of winter oilseed rape composite hybrids. *Rośliny Oleiste–Oilseed Crops* **2003**, *24*, 109–119. (In Polish)
154. Rice, P. Sulphur mustard. *Medicine* **2007**, *35*, 578–579. [CrossRef]
155. Ahmad, A.; Khan, I.; Anjum, N.A.M.; Diva, I.; Abdin, M.Z.; Iqbal, M. Effect of timing of sulfur fertilizer application on growth and yield of rapeseed. *J. Plant. Nutr.* **2005**, *28*, 1049–1059. [CrossRef]
156. Piri, I. Study of yield and yield components of black mustard (*Brassica nigra*) in condition of sulphur application and water stress. *Ann. Biol. Res.* **2012**, *3*, 2074–2077.
157. Zukalová, H.; Bečka, D.; Cihlář, P.; Mikšík, V.; Vašák, J. Quality of three types of winter rapeseed varieties. *Prosperující olejniny* **2014**, *1*, 93–97, (In Czech with English abstract).
158. Różyło, K.; Pałys, E. New oilseed rape (*Brassica napus* L.) varieties—Canopy development, yield components, and plant density. *Acta Agr. Scand. B. -S. P.* **2014**, *64*, 260–266.
159. Sikorska, A.; Gugała, M.; Zarzecka, K.; Kapela, K. The effect of biostimulants on the glucosinolate content in winter oilseed rape (*Brassica napus* L.) seeds. *Plant. Soil Environ.* **2018**, *64*, 7–12.
160. Forster, H. Influence of N and K fertilizers on the quality and yield of oil from old and new varieties of rapeseed. In Proceedings of the 13th Colloquium of the International Potash Institute, York, UK, 1977; pp. 305–310.
161. Zanetti, F.; Vamerali, T.; Mosca, G. Yield and oil variability in modern varieties of high-erucic winter oilseed rape (*Brassica napus* L. var. *oleifera*) and Ethiopian mustard (*Brassica carinata* A. Braun) under reduced agricultural inputs. *Ind. Crops. Prod.* **2009**, *30*, 265–270.

162. Wójtowicz, M.; Wielebski, F.; Czernik-Kołodziej, K. Effect of spring nitrogen fertilization on agronomical and commercial plant characters of new breeding forms of winter oilseed rape. *Rośliny Oleiste: Oilseed Crops* **2002**, *23*, 337–350. (In Polish)
163. Wójtowicz, M. Effect of nitrogen fertilization and environment conditions on biological and commercial characters of oilseed rape composite hybrids Kaszub and Mazur. *Rośliny Oleiste: Oilseed Crops* **2004**, *25*, 109–123. (In Polish)
164. Wielebski, F.; Muśnicki, C. The influence of increasing sulfur rates and sulfur application methods on the seed yield and glucosinolate content of two winter rapeseed cultivars in field experiments. *Rocz. AR Poznań* **1998**, *303*, 149–167. (In Polish)
165. Singh, M.; Kumar, M. Effect of nitrogen and sulphur levels on seed yield and some other characters in mustard (*Brassica juncea* (L.) Czern and Coss). *Int. J. Agric.* **2014**, *10*, 449–452.
166. Barczak, B.; Klikocka, H. Effect of sulphur fertilization on aminoacid and fraction composition of protein of white mustard seeds. *J. Agr. Sci. Tech.* **2018**, *20*, 1443–1453.
167. Nuttall, W.F.; Ukrainetz, H.; Stewart, J.W.B.; Spurr, D.T. The effect of nitrogen, sulphur and boron on yield and quality of rapeseed (*Brassica napus* L. and *B. campestris* L.). *Can. J. Soil Sci.* **1987**, *67*, 545–559. [CrossRef]
168. Čeh, B.; Hrastar, R.; Tajnšek, A.; Košir, I.J. Impact of source and application time of sulphur on the yield, oil content and protein content in winter oilseed rape. *Acta Agric. Slov.* **2008**, *91*, 5–14. [CrossRef]
169. Sardana, V.; Atwal, A.K. Influence of nitrogen and sulphur on seed yield and quality of hybrid canola. In Proceedings of the 12th International Rapseed Congress, Wuhan, China, 26–30 March 2007; Volume 1, pp. 243–245.
170. Liu, X.; Yang, Y.; Deng, X.; Li, M.; Zhang, W.; Zhao, Z. Effects of sulfur and sulfate on selenium uptake and quality of seeds in rapeseed (*Brassica napus* L.) treated with selenite and selenate. *Envrion. Exp. Bot.* **2017**, *135*, 13–20. [CrossRef]
171. Zukalová, H.; Matula, J.; Kuchtová, P.; Miksik, V. Influence of sulphur on the yield and quality of winter oilseed rape. *Rośliny Oleiste: Oilseed Crops* **2001**, *22*, 587–596. (In Polish)
172. Wielebski, F.; Wójtowicz, M.; Krzymański, J. Influence of sulphur fertilization on glucosinolate quality and quantity in seed of two double low oilseed rape varieties (*Brassica napus* L.). In Proceedings of the 10th International Rapeseed Congress, Canberra, Australia, 26–29 September 1999; pp. 301–316.
173. Vermorel, M.; Heaney, R.K.; Fenwick, R. Nutritive value of rapeseed meal: Effects of individual glucosinolates. *J. Sci. Food Agric.* **1986**, *37*, 1197–1202. [CrossRef]
174. Wielebski, F. Influence of sulphur fertilization and foliar application with magnesium and boron on the spring oilseed rape yield and glucosinolates content in seeds. *Rośliny Oleiste: Oilseed Crops* **1997**, *18*, 179–186. (In Polish)
175. Rotkiewicz, D.; Ojczyk, T.; Konopka, I. The influence of sulfur fertilization on the quality and processing suitability of winter rapeseed. *Rośliny Oleiste: Oilseed Crops* **1996**, *17*, 257–264. (In Polish)
176. Cardone, M.; Mazzoncini, M.; Menini, S.; Rocco, V.; Senatore, A.; Seggiani, M.; Vitolo, S. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: Agronomic evaluation, fuel production by transesterification and characterization. *Biomass Bioenerg.* **2003**, *25*, 623–636. [CrossRef]
177. Venturi, P.; Venturi, G. Analysis of energy comparison for crops in European agricultural systems. *Biomass Bioenergy* **2003**, *25*, 235–255. [CrossRef]
178. Stephenson, A.L.; Dennis, J.S.; Scott, S.A. Improving the sustainability of the production of biodiesel from oilseed rape in the UK. *Process. Saf. Environ. Prot.* **2008**, *86*, 427–440. [CrossRef]
179. Unakitan, G.; Hurma, H.; Yilmaz, F. An analysis of energy use efficiency of canola production in Turkey. *Energy* **2010**, *35*, 3623–3627. [CrossRef]
180. Mousavi-Avval, S.H.; Rafiee, S.; Jafari, A.; Mohammadi, A. Energy flow modeling and sensitivity analysis of inputs for canola production in Iran. *J. Clean. Prod.* **2011**, *19*, 1464–1470. [CrossRef]
181. Filipović, D.; Krička, T. An energy analysis of rapeseed production for biodiesel in Croatia. *J. Mech. Eng.* **2006**, *52*, 680–692.
182. Gemtos, T.A.; Cavalaris, C.; Karamoutis, C.; Tagarakis, A.; Fountas, S. Energy analysis of three energy crops in Greece. *Agric. Eng. Int. CIGR J.* **2013**, *15*, 52–66.

183. Firrisa, M.T.; Van Duren, I.; Voinov, A. Energy efficiency for rapeseed biodiesel production in different farming systems. *Energ. Effic.* **2014**, *7*, 79–95. [CrossRef]
184. Bielski, S.; Jankowski, K.J.; Budzyński, W.S. The energy efficiency of oil seed crops production and their biomass conversion into liquid fuels. *Przem. Chem.* **2014**, *93*, 2270–2273. (In Polish)