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# Oilseed Radish: Nitrogen and Sulfur Management Strategies for Seed Yield and Quality—A Case Study in Poland

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**Abstract:** Nitrogen (N) and sulfur (S) fertilization significantly affect seed yield and quality in *Brassica* oilseed crops. The effect of N and S management on the crop parameters (plant height, stem-base diameter, and number of branches), yield (seed yield components, seed and straw yields, harvest index—HI), and the quality of the seeds and oil (crude fat—CF, total protein—TP, crude fiber—CFR, fatty acids profile—FA, acid detergent fiber; and neutral detergent fiber) of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) was analyzed in the study. The effect of N and S fertilization was evaluated in a field experiment in Bałcyny (north-eastern Poland) in 2020–2022. The experiment had a split-plot design with two factors and three replications. The first factor was the N rate (0, 30, 60, 90, 120 kg ha$^{-1}$) and the second factor was the S rate (0, 15, 30 kg ha$^{-1}$). Nitrogen fertilization stimulated stem elongation and branching. The average oilseed radish (OSR) seed yield ranged from 0.59 to 1.15–1.25 Mg ha$^{-1}$. Seed yields increased significantly, up to 90 kg N ha$^{-1}$ and 15 kg S ha$^{-1}$. The N fertilizer use efficiency (NFUE) of OSR decreased with a rise in the N rate (from 4.22 to 2.19 kg of seeds per 1 kg N). The application of S did not increase NFUE. The HI ranged from 10% (0–30 kg N ha$^{-1}$) to 12% (60 kg N ha$^{-1}$). The contents of CF, TP, and CFR in OSR seeds (kg$^{-1}$ dry matter—DM) were 383–384 g, 244–249 g, and 97–103 g, respectively. Nitrogen fertilization decreased the CF content (by 5%) and increased the contents of TP (by 5%) and CFR (by 16%) in OSR seeds. Sulfur fertilizer applied at 30 kg ha$^{-1}$ decreased the CF content (by 2%), but it did not alter the content of TP or CFR. Oilseed radish oil contained 68–70% of monounsaturated FAs (MUFAs) (erucic acid accounted for 2/3 of the total MUFAs), 24–25% of polyunsaturated FAs (PUFAs), and 6–8% of saturated FAs (SFAs). Nitrogen fertilization increased the proportions of SFAs and PUFAs in OSR oil. Nitrogen rates of 60–90 kg ha$^{-1}$ increased the contents of alpha-tocopherol ($\alpha$-T), beta-tocopherol ($\beta$-T), and gamma-tocopherol ($\gamma$-T) in OSR seeds by 32%, 40%, and 27%, respectively. Sulfur fertilization increased the content of PUFAs and decreased the content of MUFAs in OSR oil, while it increased the contents of $\alpha$-T (by 15%) and $\gamma$-T (by 19%) in OSR seeds. Proper N and S management in OSR cultivation can improve crop productivity and the processing suitability of seeds.

**Keywords:** *Raphanus sativus* L.; biomass yield; fat and fatty acids; protein and fiber; tocopherols

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## 1. Introduction

The genus *Raphanus* L. consists of several plant species that are cultivated for their edible seeds (oilseed crops) and roots (vegetables) [1]. Genetic research indicates that wild radish was domesticated in at least three independent areas in the Eastern Mediterranean Region and East Asia [2–4]. Spanish radish (*Raphanus sativa* L. var. *niger* Kerner) roots were already an important part of the human diet in ancient Egypt (2000 BCE) and China (1100 BCE). In addition to root vegetables of the genus *Raphanus*, oilseed varieties, including oilseed radish—OSR (*Raphanus sativus* L. var. *oleiformis* Pers.), were also developed in China.

In the early 19th century, OSR was imported from China to Central Europe and it was first cultivated in Silesia (southern Poland) [5].

Oilseed radish is a spring annual plant of the family *Brassicaceae* that produces a strong taproot with numerous side roots that penetrate the soil to a depth of 1.5 m. The stem reaches a height of 70–120 cm and produces numerous branches in the upper part [1,6]. The structure of OSR leaves, flowers, and inflorescences is typical of the family *Brassicaceae*. The fruit consists of indivisible siliques (without sutures or a central partition) with an irregular shape (pod- and pear-shaped), a length of 2–6 cm, and a thickness of 0.4–0.5 to 1.0 cm. Siliques taper to a sharp point at the end [1,6]. Seeds with a weight of 12–20 g (thousand seed weight—TSW) are embedded in parenchymal tissue inside siliques (Scheme 1). Seed pods tend to fall to the ground without shattering, especially in dry years [1].

**Scheme 1.** Siliques (horizontal and vertical cross-sections) and seeds of oilseed radish cv. Toro.

Oilseed radish has several advantages in the production process, including (i) a short life cycle (90–120 days), (ii) low agronomic requirements, (iii) low production costs, (iv) a high oil content, and (iv) a high oil yield of cold-pressed seeds [1,7]. The crude fat (CF) content of OSR seeds ranges from 284 to 398 g $kg^{-1}$ dry matter (DM) [8–12]. Crude fat is abundant in very-long-chain fatty acids (FAs), including erucic acid ($C_{22:1}$, 18–33%) and eicosanoic acid ($C_{20:1}$, 8–11%) [11–15]. The extracted oil is characterized by high oxidative stability due to high concentrations of phytosterols and tocopherols (Ts) [16]. The content of gamma-tocopherol ($\gamma$-T) in OSR seeds (11.4 mg 100 $g^{-1}$ seeds) is comparable to that reported in rapeseed (*Brassica napus* L.), field mustard (*Brassica rapa* L.), and Indian mustard (*Brassica juncea* L./Czern.) [17]. Similarly to other plants of the family *Brassicaceae*, OSR seeds contain glucosinolates (GSLs, 120–182 $\mu$M $g^{-1}$) [7,18], including glucoraphanin (50–52% of total GSLs) and glucoerysolin (39–41% of total GSLs) [18]. Glucoraphanin is hydrolyzed directly to sulforaphane, a compound with anticarcinogenic properties [19], which removes carcinogenic chemicals and confers protection against carcinogens and inflammation in humans and animals [20]. However, high levels of $C_{20:1}$ and GSLs limit the suitability of OSR seeds for food and feed production [14,15]. A high dietary intake of $C_{20:1}$ increases the risk of cardiovascular disease [21], whereas high dietary inclusion levels of GSLs inhibit animal growth, decrease fertility, increase the risk of hyperthyroidism or hypothyroidism by disrupting iodine metabolism, exert negative effects on the cardiovascular system, and increase the risk of liver and kidney dysfunction, bronchitis, and pneumonia [22]. The contents of total protein (TP) and crude fiber (CFR) in OSR seeds range from 268 to 300 g kg$^{-1}$ DM, and from 120 to 140 g kg$^{-1}$ DM, respectively [7,9]. Oilseed radish is an ideal raw material for industrial processing due to the chemical composition of its seeds. Oilseed radish oil has numerous applications in the oleochemical [15] and petrochemical industries [23,24].

The seed yield of OSR ranges from 0.6–1.5 to even 2.0–2.9 Mg ha$^{-1}$ under supportive soil and climatic conditions [8,9,11]. In the humid continental climate of European Russia (*Dfb*—Köppen climate classification), OSR yields are comparable to crambe (*Crambe abyssinica* Hochst ex R.E. Fries) (2.4 Mg ha$^{-1}$) and exceed the yields of other *Brassica* oilseed crops by 10% (winter camelina—*Camelina sativa* L./Crantz), 16–20% (spring camelina, spring rapeseed, and oil flax—*Linum usitatissimum* L.), and 24% (white mustard—*Sinapis alba* L.) [11]. In western Poland (*Dfb*), OSR yields were 67% and 24% lower in comparison with white mustard and crambe, respectively, but they exceeded the yields of the remaining spring oilseed crops of the family *Brassicaceae* by 5% (field mustard and spring camelina) to 19–28% (spring rapeseed and Indian mustard) [8].

Plants of the family *Brassicaceae* accumulate significant quantities of TP and biologically active compounds (mainly GSLs) in seeds, and they are characterized by a high demand for fertilizers, mostly N and S [25]. *Brassica* crops have high N requirements because their seeds synthesize large amounts of TP [26]. *Brassicas* also have a high demand for S, which directly participates in the biosynthesis of sulfur-containing amino acids (cystine, cysteine, methionine) that act as precursors of biologically active compounds such as alkene GSLs, glutathione, thiamine (vitamin B1), biotin (vitamin H), coenzyme A, lipoic acid, thioredoxin, and sulfolipids [22,27–30]. Nitrogen and S fertilization significantly affect the yield and quality of seeds in *Brassica* oilseed crops, including winter rapeseed [31], camelina [32–34], Indian mustard, spring rapeseed and field mustard-type canolas, and Indian mustard and white mustard-type mustards [35]. Fertilization also has a considerable influence on energy consumption in seed production in *Brassica* oilseed crops. This agronomic operation is responsible for 53–54% of energy inputs and 75–89% of greenhouse gas emissions in the cultivation technologies of *Brassica* oilseed crops [36].

Inadequate or excess supplies of N and S can decrease seed yield and quality [37–40]. Sulfur deficiency decreases TP content, increases nitrate concentration, and promotes proteolysis in plants [41]. In turn, an adequate S supply increases nitrogen fertilizer use efficiency (NFUE) and nitrogen agronomic efficiency [41–43]. Sokólski et al. [44] demonstrated that in crambe cultivation, S fertilizer increased NFUE by 22–39%. Sulfur fertilization also increased NFUE in the production of other alternative *Brassica* crops, including camelina, white and Indian mustard, and field mustard [34,45–49]. Jankowski et al. [50] and Jankowski and Sokólski [51] found that the incorporation of S into the N fertilization regime not only increased seed yields in spring camelina and crambe but also improved energy efficiency in the production technologies of these crops.

In the scientific literature, the effect of combined N and S fertilization on the growth and development of OSR plants, seed yields, and seed quality has not yet been analyzed. The role of S in improving N agronomic efficiency in OSR cultivation has not been explored, either. The present study was undertaken to verify the following research hypotheses: (i) combined N and S fertilization promotes the growth of OSR plants and increases seed yields; (ii) the incorporation of S into the N fertilization regime increases NFUE, in particular at high rates of N fertilizer; (iii) a rise in N and S rates induces a decrease in CF content and an increase in TP and CFR contents; and (iv) S and N management modifies FA profile and T content. The objective of this study was to evaluate the effect of N and S fertilization on the parameters of OSR plants grown in north-eastern Poland (plant height, stem-base diameter, and the number of primary productive branches), OSR yields (seed yield components; seed and straw yields; and harvest index—HI), and the processing suitability of OSR seeds and oil in the oleochemical industry and in the production of biobased products (contents of CF, TP, and CFR; FA profile; content of acid detergent fiber—ADF and neutral detergent fiber—NDF; and T content).

## 2. Materials and Methods

### *2.1. Field Experiment*

A field experiment with oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) was conducted at the Agricultural Experiment Station (AES) in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, north-eastern Poland) in 2020–2022. This station is affiliated with the University of Warmia and Mazury in Olsztyn. The experiment had a split-plot design with two factors and three replications. The first factor was the N rate (0, 30, 60, 90, 120 kg ha$^{-1}$) and the second factor was the S rate (0, 15, 30 kg ha$^{-1}$). Rates up to 90 kg N ha$^{-1}$ were applied once immediately before sowing, whereas rates above 90 kg N ha$^{-1}$ were divided into two applications: an initial 90 kg ha$^{-1}$ before sowing and a subsequent 30 kg ha$^{-1}$ during BBCH stages 12–13 (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [52]). Ammonium nitrate (Pulan, Grupa Azoty SA, Puławy, Poland; 34% N) was the source of N, and potassium sulfate (KALISOP®, K+S Aktiengesellschaft, Kassel, Germany; 18% S, 41.5% K) was the source of S, which was applied immediately before sowing.

Each plot had an area of 15 m$^2$ (10 by 1.5 m). Winter wheat (*Triticum aestivum* L.) was grown as the forecrop. After harvest, the soil was skimmed (to a depth of 8–10 cm) and harrowed with a light-duty harrow. Before sowing, the soil was plowed (24–26 cm), tilled (4–6 cm), and leveled. Oilseed radish cv. Toro was sown on the following dates: 1 April 2020, 12 April 2021, and 7 April 2022, using a Promar SPZ-1.5 plot seeder (PW PROMAR Ltd. Poznań, Poland). The sowing density was 100 pure live seeds m$^2$, the row spacing was 19 cm, and the sowing depth was 2 cm. In total, 20 kg P ha$^{-1}$ (enriched superphosphate, Super Fos Dar, Grupa Azoty Fosfory Ltd., Gdańsk, Poland; 17.4% P) and 83 kg K ha$^{-1}$ were applied immediately before sowing. In treatments without S fertilization, potassium was applied only as potash salt (60er Kali® gran., K+S Aktiengesellschaft, Kassel, Germany; 50% K). In treatments with S fertilization, potassium sulfate (KALISOP®, K+S Aktiengesellschaft, Kassel, Germany; 18% S, 41.5% K) was applied to balance the S rate (15 or 30 kg ha$^{-1}$). When 15 kg S ha$^{-1}$ was applied as potassium sulfate, 34.6 kg K ha$^{-1}$ was supplied to the soil. In these treatments, potash salt was applied at 48.4 kg K ha$^{-1}$ to achieve the desired K rate. When 30 kg S ha$^{-1}$ was applied as potassium sulfate, 69.2 kg K ha$^{-1}$ was supplied to the soil. In these treatments, potash salt was applied at 13.8 kg K ha$^{-1}$ to achieve the desired K rate. Dicotyledonous weeds were controlled using metazachlor (800 g ha$^{-1}$), applied two or three days post-sowing. Insecticides were applied four times during the growing season: (i) 5 g ha$^{-1}$ of deltamethrin (BBCH 52), (ii) 20 g ha$^{-1}$ of acetamiprid + 6 g ha$^{-1}$ of lambda-cyhalothrin (BBCH 55), and (iii) 60 g ha$^{-1}$ of thiacloprid + 6 g ha$^{-1}$ of deltamethrin (BBCH 60). Fluopyram at 125 g ha$^{-1}$ and prothioconazole at 125 g ha$^{-1}$ were applied in BBCH stages 66–67 to protect plants against pathogens. The plots were not irrigated. Oilseed radish was harvested in BBCH stage 89 (05–17 August) using a small-plot harvester (Wintersteiger Classic, type 1540–447, Ried im Innkreis, Austria).

The experiment was established on Haplic Luvisol originating from boulder clay [53]. In each year of the study, soil samples were collected (0–20 cm depth) before fertilization and sowing to determine the chemical properties of the soil. Composite samples were made by combining 10 cores from each plot. The soil pH ranged from 6.2 to 6.4 and the soil nutrient levels ranged from 11.1 to 12.2 g kg$^{-1}$ of $C_{org}$, 1.12–1.32 g kg$^{-1}$ of $N_{total}$, 37.5–62.8 mg kg$^{-1}$ of P, 112.1–166.0 mg kg$^{-1}$ of K, 43.0–61.0 mg kg$^{-1}$ of Mg, and 2.4–6.9 mg kg$^{-1}$ of $SO_4^{2-}$. The methods used for evaluating the chemical properties of the soil were described by Jankowski et al. [34].

### *2.2. Weather Conditions*

In each year of the experiment (2020–2022), the growing seasons (April–August) differed in precipitation levels and temperature (Figure 1). In the first year of the study, the mean daily temperatures were comparable with the long-term average (14.6 °C). In years 2 and 3, the mean daily temperatures in April–August were 0.5 °C above the long-term average. In general, between sowing and bud formation (April and May), the mean daily temperatures were lower than the long-term average (by 0.9–2.1 °C and 1.2–3.2 °C, respectively). In successive stages of plant growth (June, July, and August), the mean daily temperatures were 2.0–3.5 °C, 0.6–2.8 °C, and 0.5–2.9 °C above the long-term average, respectively.

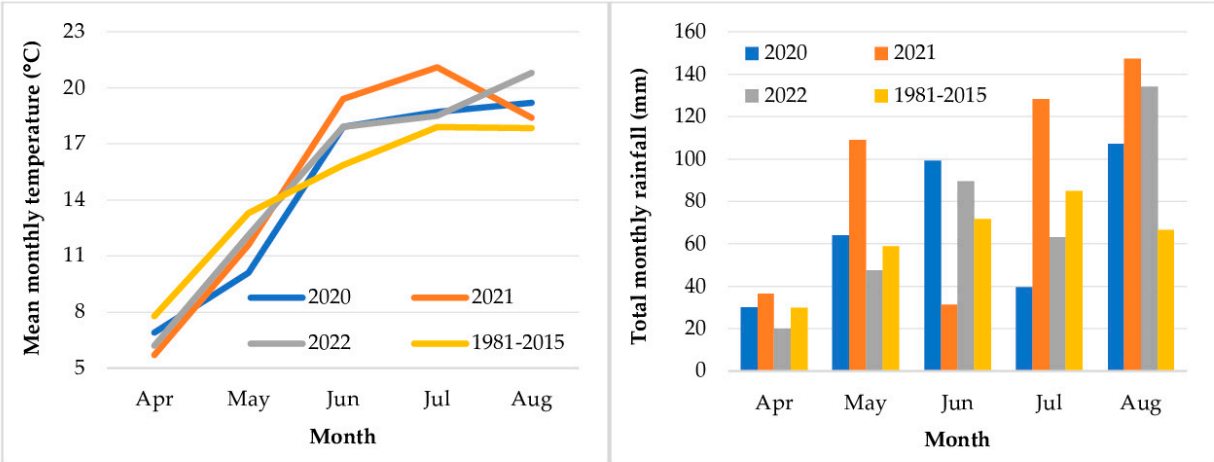


**Figure 1.** Weather conditions during the growing season of oilseed radish in 2020–2022 and the long-term average (1981–2015). Meteorological data were acquired from the PM Ecology automatic weather station (PM Ecology Ltd., Gdynia, Poland) in the AES in Bałcyny.

The analyzed growing seasons were characterized by much greater variations in precipitation levels and rainfall distributions. In the first and third years of the study, the total rainfall in April–August slightly exceeded (9–14%) the long-term average (311 mm). Precipitation levels were most favorable in the second year of the study. In this growing season, precipitation was 45% higher in comparison with the long-term average. The rainfall distribution in spring and summer also differed significantly from the long-term average. The rainfall distribution was least favorable in the third year of the experiment when precipitation levels were below the long-term average in April (by 33%), May (by 19%), and July (by 25%). In the first and second years of the study, the total rainfall was below the long-term average only in July (by 53%) or June (by 56%) (Figure 1).

### *2.3. Parameters Determined in the Field*

The main crop parameters (plant height, stem-base diameter, and the number of productive branches) and yield components (plants $m^{-2}$, siliques $plant^{-1}$, and seeds $silique^{-1}$) were determined in BBCH stages 80–82. To estimate stand density (plants $m^{-2}$), OSR plants were counted in a 5 × 1 m section of each of the two middle rows. Plant height, stem-base diameter, and the number of productive branches were determined in 10 plants sampled from each plot. The number of siliques $plant^{-1}$ was counted in 10 plants in each experimental treatment, and 50 siliques were sampled from the two middle rows to determine the number of seeds $silique^{-1}$. In each plot, TSW, seed yield, and straw yield were determined after harvest. The obtained values were converted to 91%, 91%, and 86% DM, respectively. The DM content of seed and straw biomass was calculated with the use of Equation (1). Seed and straw samples of 1 kg each were dried in an FD 53 oven (Binder GmbH, Tuttlingen, Germany) until a constant weight was reached. The harvest index (HI) was calculated with Equation (2):

$$\mathrm{DM}\ (\%) = \frac{\mathrm{M_d}}{\mathrm{M_w}} \times 100 \quad (1)$$

where

$M_d$—dry sample weight, after drying (g).
$M_w$—wet sample weight, before drying (g),

$$HI = \frac{\text{Seed yield}\left(\text{Mg DM ha}^{-1}\right)}{\text{Seed and straw yield}\left(\text{Mg DM ha}^{-1}\right)} \times 100 \quad (2)$$

NFUE was calculated with the use of Equation (3) [35]:

$$NFUE = \frac{\text{Seed yield in N treatments}\left(\text{kg ha}^{-1}\right) - \text{Seed yield intreatment swithout N}\left(\text{kg ha}^{-1}\right)}{\text{N rate}\left(\text{kg ha}^{-1}\right)} \quad (3)$$

### *2.4. Seed Quality*

The quality of OSR seeds was evaluated based on the following parameters: the contents of CF, TP, and CFR (g kg$^{-1}$ DM seeds); the contents of NDF and ADF (%); FA profile (%); and the content of Ts (mg 100 g$^{-1}$ seeds). The procedures for analyzing the contents of CF, TP, CFR, NDF, and ADF, and the FA profile were described previously by Jankowski et al. [34]. The contents of α-T, β-T, γ-T, and δ-T in the samples of OSR seeds were determined under limited exposure to sunlight [54]. The procedures for analyzing the contents of α-T, β-T, γ-T, and δ-T were described previously by Bogucka and Jankowski et al. [55].

### *2.5. Statistical Analysis*

The data were analyzed using a three-way analysis of variance (ANOVA) for a split-split-plot design, with growing seasons as whole plots, N rates as subplots, and S rates as sub-subplots. Tukey's test (HSD) was used for multiple post hoc comparisons. The data were regarded as statistically significant at $p \leq 0.05$. All analyses were conducted using STATISTICA software, version 13 [56]. The results of the *F*-test for fixed effects in ANOVA are presented in Table S1.

## 3. Results

### *3.1. Stand Architecture*

In OSR plants, the stem length was 92–151 cm and the stem-base diameter was 8–10 mm; each plant produced 5–8 productive branches (Table 1). The rate of OSR vegetative growth was the highest in the first year of the study (Table 1) when precipitation levels and temperatures approximated the long-term average (Figure 1). The number of productive branches was the lowest in the third year of the study (Table 1), which was characterized by low precipitation during vegetative growth (April and May) (Figure 1).

**Table 1.** Stand architecture of oilseed radish (main effect).

| Parameter | Plant Height (cm) | Stem-Base Diameter (mm) | Branches per Plant |
|---|---|---|---|
| Year | | | |
| 2020 | $150.7 \pm 8.6^{a}$ | $9.9 \pm 2.0^{a}$ | $8.2 \pm 1.8^{a}$ |
| 2021 | $92.3 \pm 7.8^{c}$ | $8.7 \pm 1.5^{b}$ | $7.0 \pm 0.7^{b}$ |
| 2022 | $102.8 \pm 6.8^{b}$ | $8.4 \pm 1.6^{b}$ | $5.3 \pm 0.5^{c}$ |
| Nitrogen rate (kg ha$^{-1}$), average for 2020–2022 | | | |
| 0 | $110.1 \pm 17.5^{b}$ | $8.7 \pm 2.1$ | $6.4 \pm 1.5^{b}$ |
| 30 | $115.2 \pm 17.7^{ab}$ | $9.1 \pm 1.6$ | $7.5 \pm 2.1^{a}$ |
| 60 | $117.1 \pm 17.7^{a}$ | $9.4 \pm 1.3$ | $6.9 \pm 1.7^{ab}$ |
| 90 | $117.1 \pm 17.0^{a}$ | $8.8 \pm 2.1$ | $6.8 \pm 1.4^{ab}$ |
| 120 | $116.8 \pm 16.4^{a}$ | $8.8 \pm 1.9$ | $6.6 \pm 1.6^{b}$ |

**Table 1.** *Cont.*

| Parameter | Plant Height (cm) | Stem-Base Diameter (mm) | Branches per Plant |
|---|---|---|---|
| Sulfur rate (kg ha$^{-1}$), average for 2020–2022 | | | |
| 0 | 115.6 ± 15.9 | 8.9 ± 1.4 | 7.0 ± 1.4 |
| 15 | 114.2 ± 17.7 | 9.0 ± 1.8 | 7.0 ± 1.8 |
| 30 | 115.3 ± 16.8 | 9.0 ± 2.2 | 6.8 ± 1.8 |

Means with the same letters do not differ significantly at $p \le 0.05$ in Tukey's test. Values without letters denote the absence of significant main effects or interactions.

Nitrogen fertilization significantly increased stem length by 5% (30 kg N ha$^{-1}$) and the number of productive branches per plant by 16% (60 kg N ha$^{-1}$), in comparison with the control treatment (without N fertilization) (Table 1). The stem length was not positively affected by N fertilizer only in the first year of the study when weather conditions were typical of north-eastern Poland (Figure 2). Sulfur fertilization had no significant influence on morphometric parameters (Table S1).

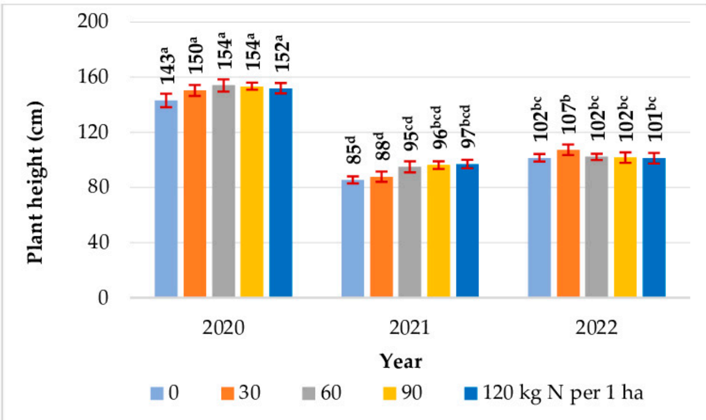


**Figure 2.** The effect of N fertilization on the height of oilseed radish plants in 2020, 2021, and 2022 (interaction). Means with the same letters do not differ significantly at $p \le 0.05$ in Tukey's test.

### *3.2. Seed Yield Components*

At harvest, the stand density ranged from 47 (2021) to 60 (2020) plants m$^{-2}$. Oilseed radish plants produced 22–35 siliques plant$^{-1}$, and each silique contained around six seeds. Thousand seed weights ranged from 14.2 to 18.4 g. The stand density and the number of seeds silique$^{-1}$ were the highest in the first year of the study. In turn, the highest number of siliques plant$^{-1}$ and the highest TSW were noted in the second and third years, respectively. A high number of siliques plant$^{-1}$ induced a decrease in TSW (year 2 vs. year 3) (Table 2).

Nitrogen fertilization increased the number of siliques plant$^{-1}$ (by 40%) (Table 2). An increase in the number of siliques plant$^{-1}$ was observed up to a N rate of 60 kg ha$^{-1}$ (years 1 and 3) or even 120 kg ha$^{-1}$ (year 2) (Figure 3). Sulfur fertilizer had no significant effect on the other yield components (plants m$^{-2}$, siliques plant$^{-1}$, and TSW) (Table S1).

**Table 2.** Yield components and the biomass yield of oilseed radish (main effect).

| Parameter | Plants m$^{-2}$ | Siliques Plant$^{-1}$ | Seeds Silique$^{-1}$ | TSW (g) | Seed Yield (Mg ha$^{-1}$) | NFUE (kg of Seeds per 1 kg N) | Straw Yield (Mg ha$^{-1}$) | Harvest Index (%) |
|---|---|---|---|---|---|---|---|---|
| Year | | | | | | | | |
| 2020 | 59.6 ± 3.9 $^a$ | 22.2 ± 3.6 $^b$ | 6.03 ± 0.40 $^a$ | 17.3 ± 0.7 $^b$ | 1.25 ± 0.17 $^a$ | 2.04 ± 0.80 $^b$ | 8.23 ± 1.48 $^b$ | 13.8 ± 2.7 $^a$ |
| 2021 | 46.9 ± 7.8 $^c$ | 34.8 ± 8.5 $^a$ | 5.70 ± 0.33 $^b$ | 14.2 ± 1.0 $^c$ | 1.16 ± 0.20 $^b$ | 6.15 ± 1.27 $^a$ | 12.03 ± 1.92 $^a$ | 10.3 ± 2.9 $^b$ |
| 2022 | 50.2 ± 4.4 $^b$ | 12.9 ± 3.3 $^c$ | 5.54 ± 0.34 $^b$ | 18.4 ± 0.6 $^a$ | 0.59 ± 0.13 $^c$ | 1.26 ± 0.38 $^b$ | 8.48 ± 1.67 $^b$ | 7.1 ± 2.0 $^c$ |
| Nitrogen rate (kg ha$^{-1}$), average for 2020–2022 | | | | | | | | |
| 0 | 51.3 ± 7.9 | 19.1 ± 8.3 $^c$ | 5.78 ± 0.40 | 16.9 ± 2.0 | 0.83 ± 0.29 $^c$ | - | 9.33 ± 1.45 $^a$ | 9.9 ± 2.5 $^b$ |
| 30 | 52.3 ± 8.7 | 22.3 ± 8.8 $^{bc}$ | 5.75 ± 0.36 | 16.8 ± 2.0 | 0.96 ± 0.36 $^b$ | 4.22 ± 0.85 $^a$ | 9.79 ± 1.33 $^b$ | 9.6 ± 2.2 $^b$ |
| 60 | 54.4 ± 6.9 | 23.3 ± 8.9 $^{ab}$ | 5.75 ± 0.43 | 16.4 ± 2.2 | 1.04 ± 0.29 $^{ab}$ | 3.43 ± 0.65 $^{ab}$ | 9.69 ± 1.24 $^b$ | 11.9 ± 1.4 $^a$ |
| 90 | 52.1 ± 7.6 | 25.0 ± 9.1 $^{ab}$ | 5.82 ± 0.48 | 16.6 ± 1.9 | 1.08 ± 0.36 $^a$ | 2.77 ± 0.69 $^{ab}$ | 9.39 ± 1.71$^a$ | 10.3 ± 2.9 $^{ab}$ |
| 120 | 51.0 ± 7.8 | 26.7 ± 9.8 $^a$ | 5.68 ± 0.40 | 16.5 ± 1.6 | 1.09 ± 0.33 $^a$ | 2.19 ± 1.06 $^b$ | 9.69 ± 1.51$^b$ | 10.2 ± 2.4 $^{ab}$ |
| Sulfur rate (kg ha$^{-1}$), average for 2020–2022 | | | | | | | | |
| 0 | 53.0 ± 7.5 | 22.7 ± 9.1 $^b$ | 5.78 ± 0.41 | 16.7 ± 2.0 | 0.96 ± 0.31 $^b$ | 4.19 ± 1.49 $^a$ | 9.50 ± 1.42 | 10.7 ± 3.3 |
| 15 | 52.5 ± 7.8 | 23.9 ± 9.4 $^a$ | 5.75 ± 0.45 | 16.6 ± 2.0 | 1.03 ± 0.35 $^a$ | 3.09 ± 1.12 $^{ab}$ | 9.59 ± 1.45 | 10.2 ± 3.1 |
| 30 | 52.2 ± 8.1 | 23.2 ± 9.5 $^{ab}$ | 5.74 ± 0.39 | 16.5 ± 1.9 | 1.00 ± 0.35 $^{ab}$ | 2.17 ± 0.98 $^b$ | 9.64 ± 1.46 | 10.3 ± 3.2 |

TSW—1000-seed weight; NFUE—nitrogen fertilizer use efficiency. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. Values without letters denote the absence of significant main effects or interactions.

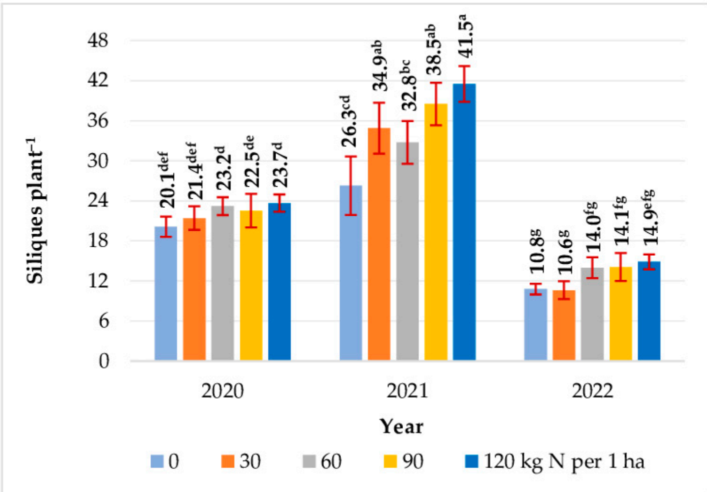


**Figure 3.** The effect of N fertilization on the number of siliques per oilseed radish plant in 2020, 2021, and 2022 (interaction). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

### *3.3. Biomass Yield and the Harvest Index*

Oilseed radish seed yields ranged from 0.59 to 1.15–1.25 Mg ha$^{-1}$, and they were the lowest in the third year of the study when the rainfall distribution during the growing season was least favorable. The N rate of 90 kg ha$^{-1}$ induced a significant ($p \leq 0.01$) increase in seed yield (by 0.25 Mg ha$^{-1}$), mainly by increasing the number of siliques plant$^{-1}$ (Table 2). There was no significant response in seed yield to N fertilization in the first year of the study (Figure 4a) when the precipitation and temperature approximated the long-term average (Figure 1). Sulfur increased seed yields (by 0.07 Mg ha$^{-1}$, i.e., 7%) up to the rate of 15 kg ha$^{-1}$ (Table 2). Sulfur did not exert a yield-forming effect only in the third year of the study when OSR seed yields were low (Figure 4b).

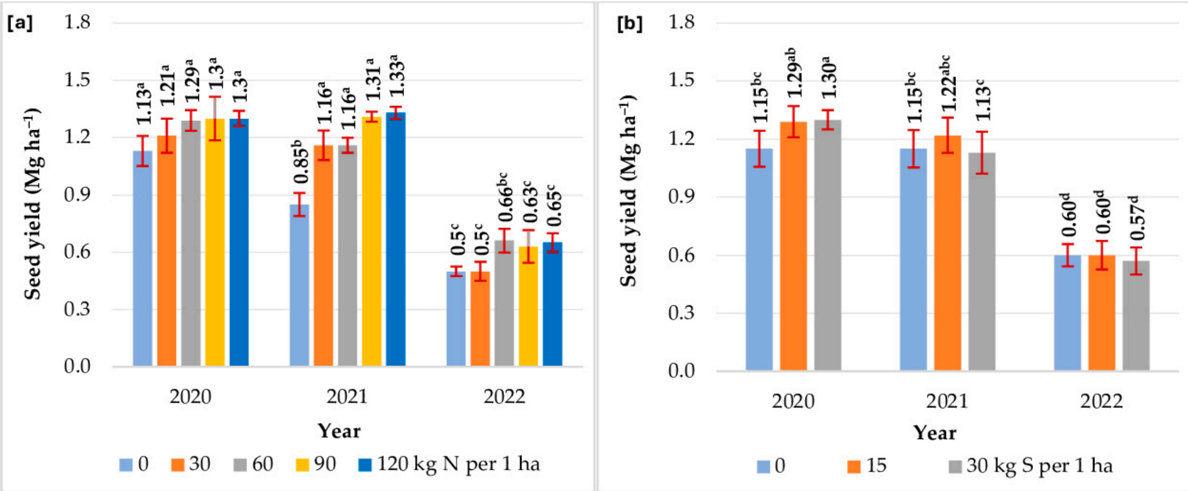


**Figure 4.** The effect of N (**a**) and S (**b**) fertilization on oilseed radish seed yields in 2020, 2021, and 2022 (interaction). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Nitrogen fertilizer use efficiency ranged from 1.06–2.04 kg (2020 and 2022) to 6.15 kg of seeds per 1 kg N (2021). On average, during the entire three-year study, NFUE was the highest after the application of 30 kg N ha$^{-1}$. Higher N rates decreased NFUE by 19–34% (60–90 kg ha$^{-1}$) to 48% (120 kg ha$^{-1}$) (Table 2). The effect of N fertilization on NFUE was modified by weather conditions (Table S1). In the first year of the study, when the precipitation approximated the long-term average, NFUE was not significantly differentiated by the tested N rates. In the second year, NFUE peaked after the application of 30 kg N ha$^{-1}$ (10.40 kg of seeds per 1 kg N). Higher N rates decreased NFUE by 51% (60–90 kg ha$^{-1}$) to 62% (120 kg ha$^{-1}$). In this growing season, the OSR seed yields were lowest in the control treatment (without N fertilization), which was the main cause for the high NFUE. In the third year, the N rate of 30 kg ha$^{-1}$ did not improve NFUE relative to the control treatment (NFUE = −0.25 kg of seeds per 1 kg N), and NFUE peaked in response to 60 kg N ha$^{-1}$ (2.67 kg of seeds per 1 kg N) (Figure 5). In this growing season, the low efficiency of N fertilizer applied at 30 kg ha$^{-1}$ could be caused by drought during the vegetative growth of OSR plants (April and May) (Figure 1). Sulfur fertilization decreased NFUE by 26% (15 kg ha$^{-1}$) and 48% (30 kg ha$^{-1}$) (Table 2), regardless of weather conditions or the applied N rate (Table S1).

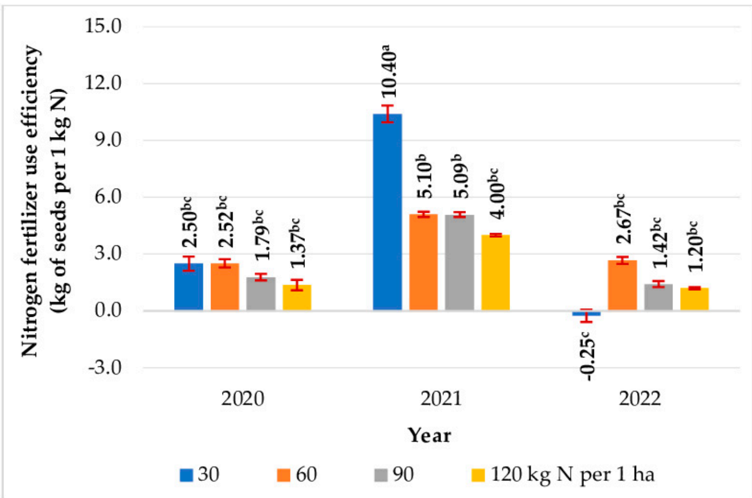


**Figure 5.** The effect of N fertilization on nitrogen fertilizer use efficiency in the production of oilseed radish in 2020, 2021, and 2022 (interaction). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Straw yields ranged from 8.23–8.48 (2020, 2022) to 12.03 Mg ha$^{-1}$ (2021). A significant increase in straw yields (5%) was observed up to the N rate of 30 kg ha$^{-1}$ (Table 2), irrespective of weather conditions (Table S1). Sulfur fertilization did not induce significant differences ($p > 0.05$) in straw yields (Table S1).

The proportion of seeds in the total biomass of OSR plants ranged from 10% to 12%. The HI increased up to a N rate of ≥60 kg ha$^{-1}$ (Table 2), irrespective of weather conditions (Table S1). The proportion of seeds in total biomass did not change significantly in response to S fertilization (Table S1).

### 3.4. Quality of Seeds and Oil

The content of CF and TP in OSR seeds was 383–384 and 244–249 g kg$^{-1}$ DM, respectively. The TP content was lowest in the third year of the study (Table 3) when the mean daily temperature in the fully ripe stage exceeded the long-term average by 2.9 °C (Figure 1). Nitrogen fertilization decreased the CF content (by 5%) and increased the TP content (by 5%) in OSR seeds. On average, during the entire three-year study, N decreased CF synthesis in OSR seeds up to the rate of 120 kg ha$^{-1}$ (Table 3). However, the negative influence of N fertilizer on the CF content of seeds was modified by weather conditions (Table S1). The CF content of seeds decreased up to a N rate of 60 kg ha$^{-1}$ in the first year, and up to a N rate of 120 kg ha$^{-1}$ in the second and third years of the experiment (Figure 6a).

**Table 3.** Nutrient contents of oilseed radish seeds (main effect).

| Parameter | Crude Fat (g kg$^{-1}$ DM) | Total Protein (g kg$^{-1}$ DM) | Crude Fiber (g kg$^{-1}$ DM) | Acid Detergent Fiber (%) | Neutral Detergent Fiber (%) |
|---|---|---|---|---|---|
| Year | | | | | |
| 2020 | 383.5 ± 15.9 | 249.0 ± 8.7 $^{a}$ | 97.4 ± 7.5 $^{b}$ | 16.8 ± 0.8 $^{a}$ | 20.9 ± 1.5 $^{a}$ |
| 2021 | 383.3 ± 11.7 | 248.5 ± 7.7 $^{a}$ | 102.6 ± 7.2 $^{a}$ | 16.9 ± 0.9 $^{a}$ | 20.4 ± 0.7 $^{b}$ |
| 2022 | 383.4 ± 10.5 | 244.2 ± 6.8 $^{b}$ | 97.6 ± 8.4 $^{b}$ | 16.0 ± 0.9 $^{b}$ | 19.7 ± 0.6 $^{c}$ |
| Nitrogen rate (kg ha$^{-1}$), average for 2020–2022 | | | | | |
| 0 | 393.3 ± 9.2 $^{a}$ | 240.6 ± 6.7 $^{d}$ | 89.1 ± 7.8 $^{c}$ | 16.6 ± 1.0 | 20.2 ± 0.9 $^{ab}$ |
| 30 | 389.8 ± 9.4 $^{a}$ | 244.5 ± 4.9 $^{cd}$ | 101.8 ± 8.4 $^{ab}$ | 16.4 ± 0.8 | 20.8 ± 1.7 $^{a}$ |
| 60 | 381.8 ± 12.3 $^{b}$ | 247.7 ± 8.0 $^{bc}$ | 106.5 ± 8.5 $^{a}$ | 16.6 ± 0.9 | 20.6 ± 0.9 $^{ab}$ |
| 90 | 380.0 ± 9.5 $^{b}$ | 249.8 ± 4.7 $^{ab}$ | 100.6 ± 6.0 $^{ab}$ | 16.5 ± 0.9 | 20.3 ± 0.9 $^{ab}$ |
| 120 | 372.2 ± 12.0 $^{c}$ | 253.7 ± 8.5 $^{a}$ | 98.0 ± 7.4 $^{b}$ | 16.7 ± 0.9 | 19.9 ± 0.8 $^{b}$ |
| Sulfur rate (kg ha$^{-1}$), average for 2020–2022 | | | | | |
| 0 | 385.8 ± 10.6 $^{a}$ | 246.5 ± 8.3 | 100.7 ± 8.9 | 16.5 ± 1.0 | 20.2 ± 0.8 |
| 15 | 386.1 ± 12.3 $^{a}$ | 246.6 ± 6.8 | 99.6 ± 8.4 | 16.7 ± 0.9 | 20.5 ± 1.5 |
| 30 | 378.4 ± 14.1 $^{b}$ | 248.6 ± 9.3 | 97.3 ± 9.0 | 16.6 ± 0.8 | 20.4 ± 0.9 |

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. Values without letters denote the absence of significant main effects or interactions.

Nitrogen increased the concentration of TP in OSR seeds up to the rate of 120 kg ha$^{-1}$ (Table 3), irrespective of weather conditions (Table S1). The CF content of seeds decreased by 2% when S was applied at 30 kg ha$^{-1}$ (Table 3). Sulfur did not induce significant differences in the TP content of seeds (Table S1). The CFR content of OSR seeds ranged from 97 to 103 g kg$^{-1}$ DM, and the proportions of ADF and NDF were 16–17% and 20–21%, respectively (Table 3). The CFR content was significantly higher (5%) in the seeds harvested in the second year. The CFR content increased by 20% in response to a N rate of 60 kg ha$^{-1}$ (Table 3), regardless of weather conditions or the applied S rate (Table S1). Nitrogen fertilization also decreased the proportion of NDF (20.2% vs. 19.9%) (Table 3). Neither the CFR content of seeds nor the proportions of NDF and ADF were significantly influenced by S fertilization (Table S1).

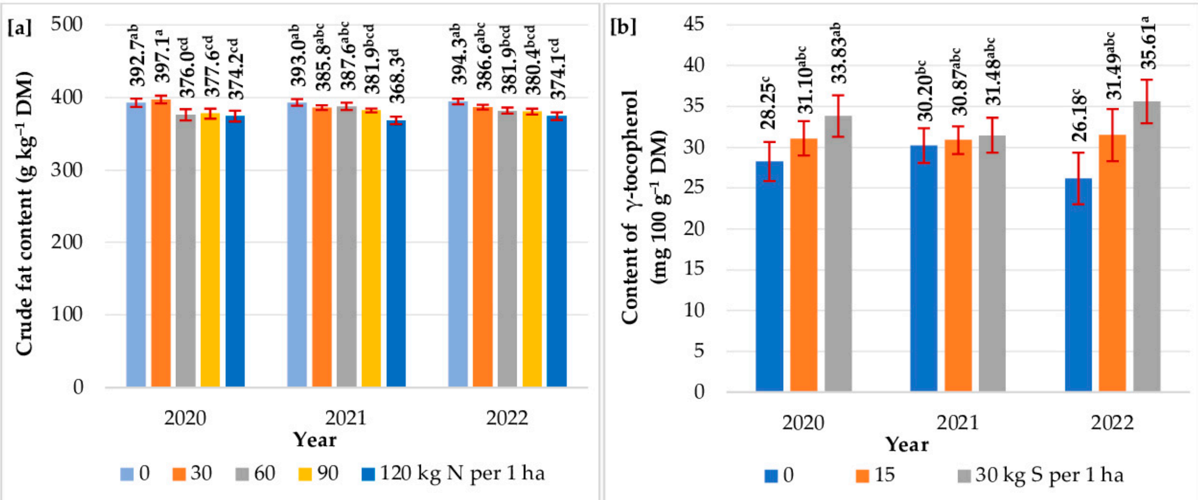


**Figure 6.** The effect of fertilization on the crude fat (**a**) and γ-tocopherol (**b**) content of oilseed radish seeds in 2020, 2021, and 2022 (interaction). Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test.

Eicosanoic acid ($C_{20:1}$) was the main FA in OSR oil (42–46%). Oilseed radish oil also contained oleic acid ($C_{18:1}$, 19–22%), linoleic acid ($C_{18:2}$, 12–13%), and linolenic acid ($C_{18:3}$, 11–12%) (Table 4). The highest content of saturated fatty acids–SFAs (palmitic acid, $C_{16}$, and stearic acid, $C_{18}$) in oil was noted in the second year of the experiment (Table 4), which was characterized by high mean daily temperatures in June and July (flowering and beginning of ripening) and average temperatures in August (fully ripe stage) (Figure 1). The content of monounsaturated fatty acids (MUFAs) in OSR oil was the highest in the third year of the study (Table 4) when mean daily temperatures were high in June, July, and August (Figure 1). In this year, OSR oil was the most abundant in MUFAs due to the increased synthesis of $C_{20:1}$ (Table 4). The content of polyunsaturated fatty acids (PUFAs) in OSR oil was the highest in the first year (Table 4) when mean daily temperatures and precipitation approximated the long-term average (Figure 1). Weather conditions in the first year of the experiment promoted the biosynthesis of $C_{18:2}$ and $C_{18:3}$. Nitrogen fertilization increased the proportion of SFAs and PUFAs in OSR oil. The content of SFAs ($C_{16}$ and $C_{18}$) increased up to a N rate of 90 kg ha$^{-1}$. In turn, PUFA concentrations ($C_{18:3}$) increased up to a N rate of 30 kg ha$^{-1}$ (Table 4). The application of 30 kg N ha$^{-1}$ contributed to a significant decrease in the content of $C_{22:1}$ and an increase in the content of $C_{20:1}$ (total MUFAs did not change) (Table 4). Sulfur fertilization significantly decreased the proportion of MUFAs and increased the proportion of PUFAs in OSR oil (Table 4).

Oilseed radish seeds contained 34.1–35.7 (2020, 2022) to 36.6 mg 100 g$^{-1}$ DM Ts (2021), mostly γ-T (84–91%) (Table 5). In all the years of the study, weather conditions induced significant differences in the content of α-, β-, and δ- homologs of T. Tocopherol levels in OSR seeds were the highest in the second year. The content of γ-T, the dominant T, was not affected by weather conditions. The content of total Ts increased significantly (by 28%) in response to a N rate of 90 kg ha$^{-1}$. Nitrogen increased the concentrations of α-T, β-T, and γ-T by 32%, 40%, and 27%, respectively. Sulfur fertilization at 30 kg$^{-1}$ increased the contents of α-T, γ-T, and total Ts by 15%, 19%, and 15%, respectively (Table 5). The positive effect of S on γ-T was not observed only in the first year of the study (Figure 6b). The influence of N fertilization on Ts levels in OSR seeds was not dependent on the supply of S (N × S interaction was not significant) (Table S1).

**Table 4.** Fatty acid composition in oilseed radish oil (%) (main effect).

| Parameter | $C_{16}$ | $C_{18}$ | $C_{18:1}$ | $C_{18:2}$ | $C_{18:3}$ | $C_{20:1}$ | $C_{22:1}$ | SFAs | MUFAs | PUFAs |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Year | | | | | |
| 2020 | 5.03 ± 0.23 $^{a}$ | 2.09 ± 0.57 $^{b}$ | 21.52 ± 1.87 $^{a}$ | 12.78 ± 0.97 $^{a}$ | 11.82 ± 0.93 $^{a}$ | 0.87 ± 0.17 $^{b}$ | 45.88 ± 2.05 $^{a}$ | 7.11 ± 0.91 $^{b}$ | 68.29 ± 1.20 $^{b}$ | 24.60 ± 1.35 $^{a}$ |
| 2021 | 5.01 ± 0.22 $^{a}$ | 2.99 ± 0.58 $^{a}$ | 22.02 ± 1.85 $^{a}$ | 12.99 ± 0.59 $^{a}$ | 11.01 ± 1.01 $^{b}$ | 0.65 ± 0.12 $^{c}$ | 45.33 ± 2.17 $^{a}$ | 7.99 ± 1.24 $^{a}$ | 68.01 ± 1.34 $^{b}$ | 24.00 ± 0.95 $^{b}$ |
| 2022 | 4.45 ± 0.20 $^{b}$ | 2.01 ± 0.79 $^{b}$ | 18.99 ± 1.42 $^{b}$ | 12.09 ± 0.52 $^{b}$ | 11.79 ± 1.03 $^{a}$ | 8.41 ± 0.28 $^{a}$ | 42.28 ± 1.59 $^{b}$ | 6.44 ± 1.06 $^{c}$ | 69.66 ± 1.80 $^{a}$ | 23.88 ± 1.18 $^{b}$ |
| | | | | | Nitrogen rate (kg ha$^{-1}$), average for 2020–2022 | | | | | |
| 0 | 4.81 ± 0.37 $^{ab}$ | 2.10 ± 0.85 $^{bc}$ | 19.99 ± 1.92 $^{b}$ | 12.64 ± 0.89 | 11.74 ± 0.95 $^{ab}$ | 3.20 ± 0.61 $^{b}$ | 45.51 ± 2.55 $^{a}$ | 6.91 ± 1.15 $^{b}$ | 68.70 ± 2.09 | 24.39 ± 1.08 $^{ab}$ |
| 30 | 4.88 ± 0.25 $^{ab}$ | 1.92 ± 0.64 $^{c}$ | 20.96 ± 1.97 $^{ab}$ | 12.70 ± 0.88 | 12.10 ± 1.26 $^{a}$ | 3.41 ± 0.75 $^{a}$ | 44.03 ± 2.45 $^{b}$ | 6.80 ± 0.86 $^{a}$ | 68.40 ± 1.23 | 24.80 ± 1.26 $^{a}$ |
| 60 | 4.82 ± 0.38 $^{ab}$ | 2.38 ± 0.92 $^{abc}$ | 20.48 ± 1.79 $^{ab}$ | 12.63 ± 0.65 | 11.46 ± 0.96 $^{bc}$ | 3.33 ± 0.71 $^{a}$ | 44.90 ± 2.72 $^{ab}$ | 7.20 ± 1.34 $^{ab}$ | 68.71 ± 1.25 | 24.09 ± 1.08 $^{abc}$ |
| 90 | 4.90 ± 0.35 $^{a}$ | 2.79 ± 0.97 $^{a}$ | 21.23 ± 1.81 $^{a}$ | 12.60 ± 0.66 | 11.38 ± 0.64 $^{bc}$ | 3.29 ± 0.64 $^{ab}$ | 43.74 ± 2.21 $^{b}$ | 7.65 ± 1.53 $^{a}$ | 68.33 ± 1.29 | 23.98 ± 1.05 $^{bc}$ |
| 120 | 4.73 ± 0.34 $^{b}$ | 2.61 ± 0.84 $^{ab}$ | 21.56 ± 1.73 $^{a}$ | 12.52 ± 0.98 | 11.02 ± 1.10 $^{c}$ | 3.32 ± 0.71 $^{ab}$ | 44.31 ± 2.35 $^{ab}$ | 7.34 ± 1.16 $^{ab}$ | 69.11 ± 2.04 | 23.54 ± 1.24 $^{c}$ |
| | | | | | Sulfur rate (kg ha$^{-1}$), average for 2020–2022 | | | | | |
| 0 | 4.80 ± 0.33 | 2.20 ± 0.88 | 20.96 ± 1.95 | 12.56 ± 0.84 | 11.29 ± 0.72 $^{b}$ | 3.32 ± 0.67 | 44.86 ± 2.28 | 7.01 ± 1.16 | 69.13 ± 1.85 $^{a}$ | 23.85 ± 1.14 $^{b}$ |
| 15 | 4.83 ± 0.31 | 2.46 ± 0.90 | 21.02 ± 1.49 | 12.63 ± 0.66 | 11.54 ± 0.97 $^{ab}$ | 3.31 ± 0.69 | 44.26 ± 2.75 | 7.24 ± 1.16 | 68.55 ± 1.27 $^{ab}$ | 24.17 ± 1.23 $^{ab}$ |
| 30 | 4.85 ± 0.38 | 2.41 ± 0.94 | 20.55 ± 1.04 | 12.67 ± 0.93 | 11.79 ± 1.34 $^{a}$ | 3.30 ± 0.61 | 44.38 ± 2.49 | 7.29 ± 1.42 | 68.27 ± 1.62 $^{b}$ | 24.46 ± 1.19 $^{a}$ |

$C_{16}$—palmitic acid; $C_{18}$—stearic acid; $C_{18:1}$—oleic acid; $C_{18:2}$—linoleic acid; $C_{18:3}$—linolenic acid; $C_{20:1}$—eicosanoic acid; $C_{22:1}$—erucic acid; SFAs—saturated fatty acids; MUFAs—monounsaturated fatty acids; PUFAs—polyunsaturated fatty acids. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. Values without letters denote the absence of significant main effects or interactions.

**Table 5.** Tocopherols content of oilseed radish seeds (mg 100 $g^{-1}$ DM) (main effect).

| Parameter | α-Tocopherol | β-Tocopherol | γ-Tocopherol | δ-Tocopherol | Σ Tocopherols |
|---|---|---|---|---|---|
| Year | | | | | |
| 2020 | 1.00 ± 0.28 $^{b}$ | 3.42 ± 0.83 $^{b}$ | 31.06 ± 5.14 | 0.25 ± 0.05 $^{b}$ | 35.72 ± 5.74 $^{ab}$ |
| 2021 | 1.34 ± 0.35 $^{a}$ | 4.12 ± 0.91 $^{a}$ | 30.85 ± 3.94 | 0.28 ± 0.06 $^{a}$ | 36.59 ± 4.58 $^{a}$ |
| 2022 | 0.39 ± 0.12 $^{c}$ | 2.38 ± 0.56 $^{c}$ | 31.09 ± 7.07 | 0.20 ± 0.06 $^{c}$ | 34.06 ± 7.12 $^{b}$ |
| Nitrogen rate (kg $ha^{-1}$), average for 2020–2022 | | | | | |
| 0 | 0.74 ± 0.30 $^{b}$ | 2.63 ± 0.81 $^{c}$ | 27.37 ± 4.38 $^{c}$ | 0.23 ± 0.07 | 30.98 ± 4.84 $^{c}$ |
| 30 | 0.86 ± 0.40 $^{ab}$ | 3.04 ± 0.88 $^{bc}$ | 29.18 ± 5.01 $^{bc}$ | 0.24 ± 0.07 | 33.31 ± 5.14 $^{bc}$ |
| 60 | 0.98 ± 0.49 $^{a}$ | 3.42 ± 1.05 $^{ab}$ | 31.72 ± 3.73 $^{ab}$ | 0.25 ± 0.07 | 36.36 ± 3.79 $^{ab}$ |
| 90 | 1.05 ± 0.61 $^{a}$ | 3.69 ± 1.06 $^{a}$ | 34.81 ± 6.12 $^{a}$ | 0.27 ± 0.06 | 39.81 ± 6.51 $^{a}$ |
| 120 | 0.92 ± 0.50 $^{ab}$ | 3.74 ± 1.09 $^{a}$ | 31.93 ± 5.13 $^{ab}$ | 0.24 ± 0.06 | 36.83 ± 5.23 $^{ab}$ |
| Sulfur rate (kg $ha^{-1}$), average for 2020–2022 | | | | | |
| 0 | 0.85 ± 0.45 $^{b}$ | 3.29 ± 1.03 | 28.21 ± 5.34 $^{c}$ | 0.25 ± 0.07 | 32.60 ± 6.34 $^{c}$ |
| 15 | 0.90 ± 0.48 $^{ab}$ | 3.19 ± 1.01 | 31.15 ± 4.72 $^{b}$ | 0.25 ± 0.06 | 35.48 ± 5.06 $^{b}$ |
| 30 | 0.98 ± 0.49 $^{a}$ | 3.44 ± 1.13 | 33.64 ± 5.10 $^{a}$ | 0.23 ± 0.06 | 38.29 ± 5.07 $^{a}$ |

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. Values without letters denote the absence of significant main effects or interactions.

## 4. Discussion

### *4.1. Biomass Yield*

In European Russia (Eastern Europe), OSR yields ranged from 1.6 to even 2.4 Mg $ha^{-1}$ [11,57], and they were higher (2.56–2.90 Mg $ha^{-1}$) in Central-Eastern Europe (Poland, Lithuania) [8,9]. In a 20-year study (1978–1998) conducted in western Poland by Toboła and Muśnicki [8], the average OSR seed yield was 1.11 Mg $ha^{-1}$. In the present three-year experiment (2020–2022), the average OSR seed yield reached 1.0 Mg $ha^{-1}$ (0.59 to 1.15–1.25 Mg $ha^{-1}$). According to Toboła and Muśnicki [8], OSR, white mustard, and Indian mustard grown in Poland are characterized by very low variations in seed yields (52%, 31%, and 41%, respectively). Therefore, OSR belongs to the group of spring *Brassica* oilseed crops that are best adapted to the Polish climate.

The present study demonstrated that OSR is not only a valuable source of seeds (1.0 Mg $ha^{-1}$) for the oleochemical and petrochemical industries but also an important source of straw (8.23–12.03 Mg $ha^{-1}$) for agricultural use and energy generation. The straw yield obtained in this study is higher than that reported by Lima et al. [58] and Pegoraro et al. [59] for the agroecological conditions of Brazil (3.2–5.7 Mg $ha^{-1}$ DM). The study also revealed that the HI of OSR cultivated in north-eastern Poland is relatively low (0.07–0.14). In a previous experiment performed in north-eastern Poland, the HI of OSR was similar to that of Indian mustard (0.13) and spring rapeseed (0.17) (Table 2 vs. [60]). The proportion of seeds in total biomass is much higher in other spring *Brassica* oilseed crops grown in north-eastern Poland. The HI reached 36–48% in spring camelina [34], 35–48% in crambe [44], and 25% in white mustard [60].

Oilseed radish has similar nutrient and soil requirements to spring *Brassica* crops (camelina, crambe, rapeseed, white mustard, and Indian mustard), which have higher demands for N and S than other groups of crops (cereals, legumes, etc.) [61]. Despite the above, *Brassica* oilseed crops are characterized by relatively low N and S use efficiencies [40]. In studies of spring *Brassica* oilseed crops, NFUE (kg of seeds per 1 kg N) was determined at 6.2–13.3 in camelina [34,62]; 18.8–26.4 in Indian mustard, white mustard, field mustard, and rapeseed; 6.7–14.9 in Ethiopian mustard (*Brassica carinata* A. Braun) [32]; and 2.1–5.9 in crambe [44]. By comparison, the NFUE of common wheat ranges from 33 to 47 kg of kernels per 1 kg of N [63,64]. In the present study, the NFUE of OSR ranged from 1.26–2.04 to 6.15 kg of seeds per 1 kg of N, depending on weather conditions. This parameter was highest (6.15 kg of seeds per 1 kg of N) in the second year of the experiment when precipitation was 45% above the long-term average. The N fertilizer use efficiency was 3–5 times lower in years when precipitation levels approximated (year 1) or somewhat exceeded the long-term average (year 3). Gan et al. [35] and Johnson et al. [32] also found that weather conditions (precipitation in June and July) and soil parameters (content of mineral N in soil) influenced the NFUE of *Brassica* oilseed crops (Indian mustard, rapeseed, and field mustard-type canolas, and Indian mustard-, white mustard-, and Ethiopian mustard-type mustards). In the current study, an increase in the N rate from 0 to 120 kg ha$^{-1}$ decreased NFUE by 48% (4.22 vs. 2.19 kg of seeds per 1 kg of N). Higher N rates also decreased NFUE in the production of camelina [34,62], crambe [44], white and Indian mustards (regardless of grade), field mustard, spring rapeseed [35], and winter rapeseed [43].

In the present study, OSR was grown on Haplic Luvisols originating from boulder clay with a S content of 2.4–6.9 mg of $SO_4^{2-}$ kg$^{-1}$ (low S content according to Panak [65]). Seed yields increased (by 5%) up to the S rate of 15 kg ha$^{-1}$, mainly due to sulfur's positive impact on the number of siliques plant$^{-1}$. According to Zhao et al. [66], *Brassica* oilseed crops require 15–20 kg of S per 1 Mg of seeds. In this study, the inclusion of S in the fertilization regime of OSR decreased NFUE by 19–34% (60–90 kg N ha$^{-1}$) to 48% (120 kg N ha$^{-1}$). The negative effect of S fertilization on NFUE was exacerbated by an increase in the N rate, which could be attributed to the relatively low NFUE of OSR (in the first and third years of the study, seed yields increased by only 1.06 and 2.04 kg, respectively, per 1 kg of N). Combined S and N fertilization also exerted a weak effect on the NFUE (at 30 and 40 kg N ha$^{-1}$) of spring camelina [51] and crambe [44]. In spring *Brassica* oilseed crops, S fertilization improves NFUE only if the applied N rate is highly effective. Such observations were made by Lošák et al. [47], Jiang et al. [48], Wysocki et al. [49], and Jankowski et al. [34] in camelina; by Ahmad et al. [45] in Indian mustard and field mustard; by Kovács et al. [46] in white mustard; by Sokólski et al. [44] in crambe; and by Wielebski et al. [43] in winter rapeseed.

### *4.2. Quality of Seeds and Oil*

Oilseed radish seeds are widely used in the oleochemical and petrochemical industries due to their high CF content and FA composition [10,12–16,23,24]. In Poland, OSR seeds accumulate 284 to 398 g of CF kg$^{-1}$ DM ([8]; present study, Table 3). The CF content of OSR seeds produced in Lithuania (cv. VB Gausiai) and the central part of European Russia was 373 and 326 g kg$^{-1}$ DM, respectively [9,11]. The FA composition of OSR oil is highly variable. The predominant FA is $C_{22:1}$ (18–33%), followed by $C_{18:1}$ (24–35%), $C_{18:2}$ (8–18%), $C_{20:1}$ (8–11%), and $C_{18:3}$ (5–16%) [11–15]. Some OSR cultivars/genotypes have a very low content of $C_{22:1}$ (1.1–1.2%) [9,23] or synthesize behenic acid ($C_{22:0}$) instead of $C_{22:1}$ [10]. In the present study, $C_{22:1}$ accounted for 42–46% of the FAs identified in OSR oil. However, $C_{22:1}$ was synthesized at the expense of $C_{18:1}$ (19–22%). Similarly to high-erucic acid rapeseed (HEAR) (47–50% $C_{22:1}$) [67], traditional varieties of white and Indian mustards (55% and 37% $C_{22:1}$, respectively) [68,69], crambe (57–65% $C_{22:1}$) [56], and Ethiopian mustard (41–50% $C_{22:1}$) [67], OSR cv. Toro is highly suited for industrial processing due to a very high content of $C_{22:1}$. The contents of TP and CFR in OSR seeds were determined in the range of 268–300 and 120–140 g kg$^{-1}$ DM, respectively [7,9]. In the current study, the seeds of OSR cv. Toro were characterized by the below-average contents of TP and CFR (244–249 and 97–103 g kg$^{-1}$ DM, respectively).

Climate, environmental conditions, and production technology strongly influence the plant genotype and induce variations in the quality of OSR seeds and oil (the contents of CF, TP, and CFR and the FA profile). In most *Brassica* oilseed crops, genetically encoded seed quality traits can be modified by agronomic treatments (mostly N and S fertilization) [34,44,61,70]. Nitrogen fertilization generally decreases CF levels and increases TP concentration in seeds. The above relationship was observed in rapeseed [31,71], camelina [34,47,48], Indian mustard [72], white mustard [46], crambe [44], and OSR [this study, Table 3]. In the current experiment, N fertilizer increased the levels of SFAs ($C_{16}$ and $C_{18}$) and PUFAs ($C_{18:3}$) up to the rate of 90 and 30 kg ha$^{-1}$, respectively. Nitrogen fertilization did not lead to differences in the total content of MUFAs. In camelina oil, N fertilization decreased the proportion of MUFAs [48,73] and increased the proportion of PUFAs [48]. Nitrogen fertilization did not affect the proportions of SFAs, MUFAs, or PUFAs in Abyssinian oil [44].

In comparison with N, S fertilization exerts a more ambiguous effect on the concentrations of CF and TP in the seeds of *Brassica* oilseed crops. In the work of Jankowski et al. [74], Šiaudinis [75], Lošák et al. [47], Jiang et al. [48], and Šiaudinis and Butkutė [76], S fertilization had no effect on the CF content of seeds in oilseed crops of the family *Brassicaceae* (rapeseed, white mustard, Indian mustard, and camelina). In turn, Fismes et al. [38] and Egesel et al. [77] reported that S fertilization decreased the CF content of oilseed rape seeds by 4%. Sulfur fertilization also decreased the content of CF in OSR seeds in this study. The interaction between S fertilization and the CF content of OSR seeds was not influenced by the N rate or weather conditions. In some studies, S increased the CF content of seeds in *Brassica* oilseed crops, including rapeseed [38,78–80], white and Indian mustards [72,81–83], and crambe [44]. In the present study, S fertilization significantly decreased the proportion of MUFAs and increased the concentrations of PUFAs (beneficial influence on the biosynthesis of $C_{18:3}$). Sulfur also increased the content of PUFAs in camelina oil [48,73]. In turn, S fertilization had no influence on the proportions of SFAs, PUFAs, or MUFAs in camelina and crambe oil [34,44]. In *Brassica* oilseed crops, S fertilization is more likely to affect the amino acid composition of protein (the contents of cysteine, tryptophan, and methionine) than its total content. In most studies of oilseed crops of the family *Brassicaceae*, S fertilization had no effect on the TP content of seeds ([61,75,76,80,82,83]; this study, Table 3), or induced only a minor increase in this parameter [44,74,78,79,81,83]. In the current study, the CFR content of OSR seeds was strongly correlated with the N rate. The CFR content increased by 20% in response to a N rate of 60 kg ha$^{-1}$. Nitrogen fertilization (90 kg ha$^{-1}$) also increased the CFR content of crambe seeds (by 14%) [44].

Tocopherols are naturally occurring antioxidants that contribute to the oxidative stability of vegetable oils [84,85]. Oilseed crops of the family *Brassicaceae* are a rich source of Ts [17,84–86]. Oilseed rape seeds contain 9.0–46.0 mg 100 g$^{-1}$ of Ts [17,87], with a predominance of γ-T (57–78%) and α-T (22–43%) [17,87]. Oilseed radish seeds are equally abundant in γ-T (11–12 mg 100 g$^{-1}$), but they contain far less δ-T (~1.0–1.4 mg 100 g$^{-1}$) and are practically devoid of α-T [17]. Cereal grain [85,88–90], olive (*Olea europaea* L.), and sunflower (*Helianthus annuus* L.) seeds are rich sources of α-T [85,91,92]. In turn, δ-T is the dominant isomer in pumpkin (*Cucurbita maxima* Duchesne) seed oil [93] and seed oil from plants of the family *Boraginaceae* in the genus *Borago*, such as the starflower (*Borago officinalis* L.) [85,86]. In the present study, the total content of Ts in the seeds of OSR cv. Toro was 34.1–36.6 mg 100 g$^{-1}$, including 30.9–31.1 mg of γ-T 100 g$^{-1}$ (84–91%), 0.4–1.4 mg of α-T 100 g$^{-1}$ (1–4%), 2.4–4.1 mg of β-T 100 g$^{-1}$ (7–11%), and 0.2–0.3 mg of δ-T 100 g$^{-1}$ (<1%). In general, a predominance of γ-T in OSR seeds is desirable because this isomer is a more powerful antioxidant than α-T in emulsions [91].

Nitrogen fertilization influences the content of Ts, and N deficiency decreases their biosynthesis and accumulation in seeds [94,95]. In a study by Egesel et al. [94], a N rate of 130 kg ha$^{-1}$ significantly increased the content of total rapeseed Ts (by 1.54 mg 100 g$^{-1}$ seeds), mainly by increasing the concentration of γ-T (by 1.51 mg 100 g$^{-1}$) relative to the unfertilized control treatment. Nitrogen rates higher than 130 kg ha$^{-1}$ induced a minor decrease in the content of total Ts, mainly by decreasing the concentration of α-T. In turn, in the work of Hussain et al. [95], a significant increase in the content of γ-T and total Ts in oilseed rape was observed only at a N rate of 270 kg ha$^{-1}$. In the current study, the total content of Ts in OSR seeds increased significantly (by 28%) up to a N rate of 90 kg ha$^{-1}$, mainly due to an increase in the concentrations of α-T, β-T, and γ-T (by 32%, 40%, and 27%, respectively). The highest N rate (120 kg ha$^{-1}$) did not increase the content of Ts (β-T) or even induced a minor decrease in their concentrations (α-T and γ-T). In the work of Egesel et al. [94] and Hussain et al. [95], and in the present study [Tables 2 and 5], the content of Ts in seeds of *Brassica* oilseed crops (rapeseed, OSR) peaked in response to the most productive N rates (which contributed to the highest seed yields). According to Hussain et al. [95], the relationship between N rates and the concentrations of Ts in seeds may be due to the fact that N rates affect the agronomic traits of plants, i.e., height, number of branches, number of siliques plant$^{-1}$, and number of seeds silique$^{-1}$. The numerical values of these traits are usually highest when N is applied at the optimal rates.

Sulfur belongs to the group of macronutrients that exert the strongest effect on the biosynthesis of biologically active compounds in plants of the family *Brassicaceae*. In a study by Filipek-Mazur et al. [96], the content of total Ts in spring OSR peaked in response to the S rate of 25 kg ha$^{-1}$ (elemental S) or 50 kg ha$^{-1}$ (ammonium sulfate and a mixture of ammonium nitrate and ammonium sulfate), which indicates that S enhances the biosynthesis of α-T and γ-T. In the cited study, S fertilization significantly increased the content of α-T by 58–61% (25 kg ha$^{-1}$—elemental S, or 50 kg ha$^{-1}$—ammonium sulfate) to 81–82% (50 kg ha$^{-1}$—elemental S or a mixture of ammonium nitrate and ammonium sulfate) relative to the control treatment. Sulfur fertilization increased the content of γ-T in rapeseed by 20–42%. The concentration of γ-T peaked in response to the S rate of 25 kg ha$^{-1}$ (elemental S) or 50 kg ha$^{-1}$ (sulfate sulfur) [96]. In the present study, S fertilization applied at 30 kg ha$^{-1}$ also increased the contents of α-T, γ-T, and total Ts by 15%, 19%, and 15%, respectively.

## 5. Conclusions

In north-eastern Poland, the average OSR seed yield is 1.00 Mg ha$^{-1}$. The optimal rates of N and S fertilizers in OSR production are 90 and 15 kg ha$^{-1}$, respectively. The NFUE of OSR ranges from 1.06–2.04 to 6.15 kg of seeds per 1 kg of N. NFUE peaked in response to the N rate of 30 kg ha$^{-1}$, whereas higher N rates decreased NFUE by 19–34% (60–90 kg ha$^{-1}$) or even 48% (120 kg ha$^{-1}$). The incorporation of S into the N fertilization system of OSR did not increase NFUE. Oilseed radish is characterized by very high straw yields (8.23–12.03 Mg ha$^{-1}$) and, consequently, a relatively low HI (10–12%). The proportion of seeds in total biomass yield increased in response to a N rate of ≥60 kg ha$^{-1}$. The seeds of OSR cv. Toro contained 383–384 g CF kg$^{-1}$ DM, 244–249 g TP kg$^{-1}$ DM, and 97–103 g CFR kg$^{-1}$ DM. Nitrogen fertilization decreased the CF content by 5% (120 kg N ha$^{-1}$) and increased the content of TP by 5% (120 kg N ha$^{-1}$) and CFR by 20% (60 kg N ha$^{-1}$) in OSR seeds. The CF content of seeds decreased (by 2%) in response to the S rate of 30 kg ha$^{-1}$. Erucic acid was the predominant FA in OSR oil (42–46%). Nitrogen fertilization increased the contents of $C_{16}$ (90 kg N ha$^{-1}$), $C_{18}$ (90 kg N ha$^{-1}$), $C_{18:1}$ (90–120 kg N ha$^{-1}$), $C_{18:3}$ (30 kg N ha$^{-1}$), and $C_{20:1}$ (30 kg N ha$^{-1}$) and decreased the concentration of $C_{22:1}$ (30 kg N ha$^{-1}$). Sulfur fertilization significantly decreased the proportion of MUFAs and increased the proportion of PUFAs in OSR oil. Oilseed radish is a rich source of Ts (34.1–36.6 mg 100 g$^{-1}$ DM seeds), in particular γ-T (30.8–31.1 mg 100 g$^{-1}$ DM seeds). Nitrogen fertilization increased the content of total Ts by 28% (90 kg N ha$^{-1}$), including α-T, β-T, and γ-T (by 32%, 40%, and 27%, respectively). Sulfur fertilization at 30 kg ha$^{-1}$ increased the content of total Ts by 15%, including α-T and γ-T (by 15% and 19%, respectively). Under the agroecological conditions of north-eastern Poland, the optimal N rate in OSR cultivation was 90 kg ha$^{-1}$. This rate was most productive and enabled the production of raw material characterized by high processing suitability (high TP content and high CF content of seeds, with a higher concentration of $C_{18:1}$ and a lower concentration of $C_{22:1}$, a high content of total Ts and its homologs α, β, and γ). Combined S and N fertilization did not exert a synergistic effect in OSR cultivation (no interaction between the effects of S and N on the agronomic traits of plants or the processing suitability of seeds). The yield-forming effect of S was observed up to the rate of 15 kg ha$^{-1}$. However, the higher rate of this macronutrient (30 kg S ha$^{-1}$) had a beneficial influence on the processing suitability of seeds (an increase in the concentrations of PUFAs and Ts) without compromising yields.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14050755/s1: Table S1. *F*-test statistics in ANOVA.

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## Abbreviations

| | |
|---|---|
| ADF | acid detergent fiber |
| AES | Agricultural Experiment Station |
| BBCH | Biologische Bundesanstalt, Bundessortenamt und Chemische, Industrie |
| $C_{16}$ | palmitic acid |
| $C_{18}$ | stearic acid |
| $C_{18:1}$ | oleic acid |
| $C_{18:2}$ | linoleic acid |
| $C_{18:3}$ | linolenic acid |
| $C_{20:1}$ | eicosanoic acid |
| $C_{22:1}$ | erucic acid |
| CF | crude fat |
| CFR | crude fiber |
| DM | dry matter |
| FA | fatty acid profile |
| GSLs | glucosinolates |
| HI | harvest index |
| MUFAs | monounsaturated fatty acids |
| NDF | neutral detergent fiber |
| NFUE | nitrogen fertilizer use efficiency |
| OSR | oilseed radish |
| PUFAs | polyunsaturated fatty acids |
| SFAs | saturated fatty acids |
| TP | total protein |
| TSW | thousand seed weight |
| $\alpha$-T | alpha-tocopherol |
| $\beta$-T | beta-tocopherol |
| $\gamma$-T | gamma-tocopherol |
| $\delta$-T | delta-tocopherol |
| Ts | tocopherols |

## References


1. Jankowski, K.; Bielski, S.; Szempliński, W. Industrial Crops. In *Agricultural Crops*; Szempliński, W., Ed.; Publishing House of the University of Warmia and Mazury in Olsztyn: Olsztyn, Poland, 2012; pp. 306–446. (In Polish)
2. Yamane, K.; Lü, N.L.; Ohnishi, O. Multiple origins and high genetic diversity of cultivated radish inferred from polymorphism in chloroplast simple sequence repeats. *Breed. Sci.* **2009**, *59*, 55–65. [CrossRef]
3. Warwick, S. Brassicaceae in Agriculture. In *Genetics and Genomics of the Brassicaceae*; Schmidt, R., Bancroft, I., Eds.; Springer: Gatersleben, Germany, 2011; pp. 33–66.
4. Kim, N.; Jeong, Y.M.; Jeong, S.; Kim, G.B.; Baek, S.; Kwon, Y.E.; Cho, A.; Choi, S.B.; Kim, J.; Lim, W.J.; et al. Identification of candidate domestication regions in the radish genome based on high depth resequencing analysis of 17 genotypes. *Theor. Appl. Genet.* **2016**, *29*, 1797–1814. [CrossRef]
5. Krist, S. Oilseed Radish Oil. In *Vegetable Fats and Oils*; Krist, S., Ed.; Springer: Cham, Switzerland, 2000; pp. 489–492.
6. Tsytsiura, Y. The influence of agroecological and agrotechnological factors on the generative development of oilseed radish (*Raphanus sativus* var. *oleifera* Metzg.). *Agron. Res.* **2022**, *4*, 842–880.
7. Kołodziejczyk, M.; Kulig, B. Oilseed Radish. In *Plant Cultivation–III*; Kotecki, A., Ed.; Publishing House of the Wrocław University of Environmental and Life Sciences: Wrocław, Poland, 2020; pp. 393–399. (In Polish)
8. Toboła, P.; Muśnicki, C. Yielding variability of spring sown oilseed crops of cruciferous family. *Rośliny Oleiste-Oilseed Crops* **1999**, *20*, 93–100. (In Polish)
9. Ražukas, A.; Nedzinskienė, T.L. Pašarinių ridikų (*Raphanus sativus* L. var. *oleiformis* Pers) 'VB Gausiai' auginimas sėklai ir žaliai masei. *Žemdirbzstė–Agric.* **2008**, *95*, 86–92. (In Lithuanian)
10. Faria, D.; Santos, F.; Machado, G.; Lourega, R.; Eichler, P.; de Souza, G.; Lima, J. Extraction of radish seed oil (*Raphanus sativus* L.) and evaluation of its potential in biodiesel production. *AIMS Energy* **2018**, *6*, 551–565. [CrossRef]
11. Prakhova, T.Y.; Prakhov, V.A.; Brazhnikov, V.N.; Brazhnikova, O.F. Oil seed crops-biodiversity, value and productivity. *Vol. Reg. Farm.* **2019**, *3*, 18–23.
12. Stevanato, N.; da Silva, C. Radish seed oil: Ultrasound-assisted extraction using ethanol as solvent and assessment of its potential for ester production. *Ind. Crops Prod.* **2019**, *132*, 283–291. [CrossRef]
13. Valle, P.W.P.A.; Rezende, T.F.; Souza, R.A.; Fortes, I.C.P.; Pasa, V.M.D. Combination of fractional factorial and Doehlert experimental designs in biodiesel production: Ethanolysis of *Raphanus sativus* L. var. *oleiferus* stokes oil catalyzed by sodium ethoxide. *Energ. Fuel.* **2009**, *23*, 5219–5227. [CrossRef]
14. Chammoun, N.; Geller, D.P.; Das, K.C. Fuel properties, performance testing and economic feasibility of *Raphanus sativus* (oilseed radish) biodiesel. *Ind. Crop. Prod.* **2013**, *45*, 155–159. [CrossRef]
15. Polaczek, K.; Kurańska, M. Hemp seed oil and oilseed radish oil as new sources of raw materials for the synthesis of bio-polyols for open-cell polyurethane foams. *Materials* **2022**, *24*, 8891. [CrossRef] [PubMed]
16. Shah, S.N.; Iha, O.K.; Alves, F.C.S.V.; Sharma, B.K.; Erhan, S.Z.; Suarez, P.A.Z. Potential application of turnip oil (*Raphanus sativus* L.) for biodiesel production: Physical–chemical properties of neat oil, biofuels and their blends with ultra-low sulphur diesel (ULSD). *Bio Energ. Res.* **2013**, *6*, 841–850. [CrossRef]
17. Pegg, R.B.; Amarowicz, R. Content of tocopherol isomers in oilseed radish cultivars-a short report. *Pol. J. Food Nutr. Sci.* **2009**, *59*, 129–133.
18. Budahn, H.; Peterka, H.; Schütze, W. Glucosinolate profiles of disomic rapeseed-radish chromosome addition lines. *J. Kulturpflanzen* **2011**, *63*, 104–110.
19. Gu, Z.; Guo, Q.; Gu, Y. Factors influencing glucoraphanin and sulforaphane formation in *Brassica* plants: A Review. *J. Integr. Agric.* **2012**, *11*, 1804–1816. [CrossRef]
20. Talalay, P. Chemoprotection against cancer by induction of phase 2 enzymes. *BioFactors* **2000**, *12*, 5–11. [CrossRef] [PubMed]
21. Knutsen, H.K.; Alexander, J.; Barregård, L.; Bignami, M.; Brüschweiler, B.; Ceccatelli, S.; Dinovi, M.; Edler, L.; Grasl-Kraupp, B.; Hogstrand, C.; et al. Erucic acid in feed and food. *EFSA J.* **2016**, *14*, 173.
22. Verkerk, R.; Schreiner, M.; Krumbein, A.; Ciska, E.; Holst, B.; Rowland, I.; de Schrijver, R.; Hansen, M.; Gerhäuser, 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] [PubMed]
23. Soares, C.M.; Itavo, L.C.V.; Dias, A.M.; Arruda, E.J.; Delben, A.A.S.T.; Oliveira, S.L. Forage turnip, sunflower, and soybean biodiesel obtained by ethanol synthesis: Production protocols and thermal behavior. *Fuel* **2010**, *89*, 3725–3729. [CrossRef]
24. Silveira Junior, E.G.; Barcelos, L.F.T.; Perez, V.H.; Justo, O.R.; Ramirez, L.C.; Filho, L.d.M.R.; de Castro, M.P.P. Biodiesel production from non-edible forage turnip oil by extruded catalyst. *Ind. Crops Prod.* **2019**, *139*, 111503. [CrossRef]
25. Chorol, S.; Angchok, D.; Stobdan, T. Irrigation timing as a glucosinolate alteration factor in radish (*Raphanus sativus* L.) in the Indian Trans-Himalayan region of Ladakh. *J. Food Comp. Anal.* **2021**, *100*, 103904. [CrossRef]
26. Bouchet, A.S.; Laperche, A.; Bissuel-Belaygue, C.; Snowdon, R.; Nesi, N.; Stahl, A. Nitrogen use efficiency in rapeseed. A review. *Agron. Sustain. Dev.* **2016**, *36*, 38. [CrossRef]
27. Blake-Kalff, M.M.; Harrison, K.R.; Hawkesford, M.J.; Zhao, F.J.; McGrath, S.P. Distribution of sulfur within oilseed rape leaves in response to sulfur deficiency during vegetative growth. *Plant Physiol.* **1998**, *118*, 1337–1344. [CrossRef] [PubMed]
28. Zukalová, H.; Vasak, J. The role and effects of glucosinolates of *Brassica* species—A review. *Rostlinná Výroba* **2022**, *48*, 175–180. [CrossRef]

29. Girondé, A.; Etienne, P.; Trouverie, J.; Bouchereau, A.; Le Cahérec, F.; Leport, L.; Niogret, M.F.; Nesi, N.; Carole, D.; Soulay, F.; et al. The contrasting N management of two oilseed rape genotypes reveals the mechanisms of proteolysis associated with leaf N remobilization and the respective contributions of leaves and stems to N storage and remobilization during seed filling. *BMC Plant Biol.* **2015**, *15*, 59. [CrossRef] [PubMed]
30. Kim, Y.C.; Hussain, M.; Anarjan, M.B.; Lee, S. Examination of glucoraphanin content in broccoli seedlings over growth and the impact of hormones and sulfur containing compounds. *Plant Biotech. Rep.* **2022**, *14*, 491–496. [CrossRef]
31. Groth, D.A.; Sokólski, M.M.; Jankowski, K.J. A multi-criteria evaluation of the effectiveness of nitrogen and sulfur fertilization in different cultivars of winter rapeseed—Productivity, economic and energy balance. *Energies* **2020**, *13*, 4654. [CrossRef]
32. Johnson, E.N.; Malhi, S.S.; Hall, L.M.; Phelps, S. Effects of nitrogen fertilizer application on seed yield, N uptake, N use efficiency, and seed quality of *Brassica carinata*. *Can. J. Plant Sci.* **2013**, *93*, 1073–1081. [CrossRef]
33. Berti, M.; Gesch, R.; Eynck, C.; Anderson, J.; Cermak, S. Camelina uses, genetics, genomics, production, and management. *Ind. Crops Prod.* **2016**, *94*, 690–710. [CrossRef]
34. 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]
35. Gan, Y.; Malhi, S.S.; Brandt, S.; Katepa-Mupondwa, F.; Stevenson, C. Nitrogen use efficiency and nitrogen uptake of *juncea* canola under diverse environments. *Agron. J.* **2008**, *100*, 285–295. [CrossRef]
36. Cocco, D.; Deligios, P.A.; Ledda, L.; Sulas, L.; Virdis, A.; Carboni, G. LCA study of oleaginous bioenergy chains in a Mediterranean environment. *Energies* **2014**, *7*, 6258–6281. [CrossRef]
37. Janzen, H.H.; Bettany, J.R. Sulfur nutrition of rapeseed: I. Influence of fertilizer nitrogen and sulfur rates. *Soil. Sci. Soc. Am. J.* **1984**, *48*, 100–107. [CrossRef]
38. Fismes, J.; Vong, P.C.; Guckert, A. Frossard, EInfluence 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]
39. Malhi, S.S.; Gill, K.S. Interactive effects of N and S fertilizers on canola yield and seed quality on S-deficient Gray Luvisol soils in northeastern Saskatchewan. *Can. J. Plant Sci.* **2007**, *87*, 211–222. [CrossRef]
40. 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*, 458. [CrossRef] [PubMed]
41. Jamal, A.; Moon, Y.; Abdin, M. Sulphur—A general overview and interaction with nitrogen. *Austr. J. Crop Sci.* **2010**, *4*, 523–529.
42. Salvagiotti, F.; Castellarín, J.M.; Miralles, D.J.; Pedrol, H.M. Sulfur fertilization improves nitrogen use efficiency in wheat by increasing nitrogen uptake. *Field Crops Res.* **2009**, *113*, 170–177. [CrossRef]
43. Wielebski, F.; Wójtowicz, M.; Liersch, A. Response of new forms of winter oilseed rape with modified fatty acid composition to nitrogen and sulfur fertilization. *J. Plant Nutr.* **2022**, *45*, 2360–2379. [CrossRef]
44. Sokólski, M.M.; Załuski, D.; Jankowski, K. Crambe: Seed yield and quality in response to nitrogen and sulfur—A case study in northeastern Poland. *Agronomy* **2020**, *10*, 1436. [CrossRef]
45. 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]
46. 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]
47. 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. Sect. B–Soil Plant Sci.* **2011**, *4*, 313–321.
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.; Szatkowski, A.; Kozak, M. Crambe–Energy efficiency of biomass production and mineral fertilization. A case study in Poland. *Ind. Crops Prod.* **2022**, *182*, 114918. [CrossRef]
51. Jankowski, K.J.; Sokólski, M. Spring camelina: Effect of mineral fertilization on the energy efficiency of biomass production. *Energy* **2021**, *220*, 119731. [CrossRef]
52. Meier, U. *Growth Stages of Mono- and Dicotyledonous Plants: BBCH Monograph*; Julius Kühn-Institut: Quedlinburg, Germany, 2018. Available online: https://www.julius-kuehn.de/media/Veroeffentlichungen/bbch%20epaper%20en/page.pdf (accessed on 14 January 2024).
53. IUSS Working Group WRB. *World Reference Base for Soil Resources 2022, World Soil Resources Reports*; FAO: Rome, Italy, 2022. Available online: https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf (accessed on 10 January 2024).
54. *PN–EN ISO 6867:2002*; Feedstuffs. Determination of Vitamin E by High-performance Liquid Chromatography. Polish Committee for Standardization: Warszawa, Poland, 2002.
55. Bogucka, B.; Jankowski, K. Jerusalem artichoke: Quality response to potassium fertilization and irrigation in Poland. *Agronomy* **2020**, *10*, 1518. [CrossRef]

56. *Statistica (Data Analysis Software System)*, version 13; TIBCO Software Inc.: Palo Alto, CA, USA, 2017.
57. Ukhanova, V.; Voskresensky, A.A.; Ukhanov, A.P. Comparative evaluation of the properties of vegetable oils used as bioadditives to petroleum diesel fuel. *Niva Povolzhia* **2017**, *43*, 98–105. (In Russian)
58. Lima, J.D.; Aldrighi, M.; Sakai, R.K.; Soliman, E.P.; da Silva Moraes, W. Behavior of forage turnip (*Raphanus sativus* L.) and turnip greens (*Raphanus raphanistrum* L.) as green manure. *Pesqui. Agropecu. Trop.* **2007**, *37*, 60–63. (In Portuguese)
59. Pegoraro, T.; Sampaio, S.C.; Tavares, M.H.F.; Coelho, S.R.M.; Carneiro, L.J.; Palma, D.; de Souza, C.H.W.; Guerra, J.B. Use of swine wastewater in oilseed radish crop: Agronomic and environmental aspects. *Semina Ciênci Agrár* **2014**, *35*, 2931–2943. [CrossRef]
60. 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]
61. 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]
62. Malhi, S.S.; Johnson, E.N.; Hall, L.M.; May, W.E.; Phelps, S.; Nybo, B. Effect of nitrogen fertilizer application on seed yield, N uptake, and seed quality of *Camelina sativa*. *Can. J. Soil Sc.* **2014**, *94*, 35–47. [CrossRef]
63. Rasmussen, I.S.; Dresbøll, D.B.; Thorup-Kristensen, K. Winter wheat cultivars and nitrogen (N) fertilization-effects on root growth, N uptake efficiency and N use efficiency. *Eur. J. Agron.* **2015**, *68*, 38–49. [CrossRef]
64. Savin, R.; Sadras, V.O.; Slafer, G.A. Benchmarking nitrogen utilisation efficiency in wheat for Mediterranean and non-Mediterranean European regions. *Field Crops Res.* **2019**, *241*, 107573. [CrossRef]
65. Panak, H. (Ed.) *Agricultural Chemistry*; Publishing House of the University of Agriculture and Technology in Olsztyn: Olsztyn, Poland, 1997; pp. 1–258. (In Polish)
66. 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]
67. Zanetti, F.; Vameral, T. 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. [CrossRef]
68. Ciubota-Rosie, C.; Macoveanu, M.; Fernández, C.M.; Ramos, M.J.; Pérez, A.; Moreno, A. *Sinapis alba* seed as a prospective biodiesel source. *Biomass Bioenerg.* **2013**, *51*, 83–90. [CrossRef]
69. Shyam, C.; Tripathi, M.K. Biochemical studies in Indian mustard (*Brassica juncea* L.) Czern and Coss for fatty acid profiling. *Int. J. Chem. Stud.* **2019**, *7*, 338–343.
70. Sokólski, M.; Załuski, D.; Szatkowski, A.; Jankowski, K.J. Winter oilseed rape: Agronomic management in different tillage systems and seed quality. *Agronomy* **2023**, *13*, 524. [CrossRef]
71. 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.
72. Joshi, N.L.; Mali, P.C.; Saxena, A. Effect of nitrogen and sulphur application on yield and fatty acid composition of mustard (*Brassica junceae* L.) oil. *J. Agron. Crop Sci.* **1998**, *180*, 59–63. [CrossRef]
73. Šípalová, M.; Lošák, T.; Hlušek, J.; Vollmann, J.; Hudec, J.; Filipčík, R.; Macek, M.; Kráčmar, S. Fatty acid composition of Camelina sativa as affected by combined nitrogen and sulphur fertilisation. *Afr. J. Agric. Res.* **2011**, *6*, 3919–3923.
74. Jankowski, K.J.; Budzyński, W.S.; Szymanowski, A. Effect of sulfur on the quality of winter rape seeds. *J. Elem.* **2008**, *13*, 521–534.
75. Šiaudinis, G. The effect of nitrogen and sulphur fertilisation on the elemental composition and seed quality of spring oilseed rape. *Žemdirbzstė–Agric.* **2010**, *97*, 47–56.
76. Šiaudinis, G.; Butkutė, B. Responses of spring oilseed rape seed yield and quality to nitrogen and sulfur fertilization. *Commun. Soil Sci. Plan.* **2013**, *44*, 145–157. [CrossRef]
77. Egesel, C.Ö.; Gü, 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]
78. Ahmad, A.; 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]
79. Sattar, A.; Cheema, M.A.; Wahid, M.A.; Hassan, M. Interactive effect of sulphur and nitrogen on growth, yield and quality of canola. *Crop Environ.* **2011**, *1*, 32–37.
80. Govahi, M.; Saffari, M. Effect of potassium and sulphur fertilizers and yield, yield components and seed quality of spring canola (*Brassica napus* L.) seed. *J. Agron.* **2006**, *5*, 577–582.
81. Ahmad, A.; Abdin, M.Z. Interactive effect of sulphur and nitrogen on the oil and protein contents and on the fatty acid profiles of oil in the seeds of rapeseed (*Brassica campestris* L.) and mustard (*Brassica juncea* L. Czern. and Coss.). *J. Agron. Crop Sci.* **2002**, *185*, 49–54. [CrossRef]
82. Nowak-Polakowska, H.; Czaplicki, S.; Tańska, M.; Jankowski, K. 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. Natur. Sci.* **2005**, *18*, 25–39.
83. 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]
84. Flakelar, C.L.; Adjonu, R.; Doran, G.; Howitt, J.A.; Luckett, D.J.; Prenzler, P.D. Phytosterol, tocopherol and carotenoid retention during commercial processing of *Brassica napus* (canola) oil. *Processes* **2022**, *10*, 580. [CrossRef]

85. Górnaś, P.; Baškirovs, G.; Siger, A. Free and esterified tocopherols, tocotrienols and other extractable and non-extractable tocochromanol-related molecules: Compendium of knowledge, future perspectives and recommendations for chromatographic techniques, tools, and approaches used for tocochromanol determination. *Molecules* **2022**, *27*, 6560. [CrossRef]
86. Siger, A.; Górnaś, P. Free tocopherols and tocotrienols in 82 plant species' oil: Chemotaxonomic relation as demonstrated by PCA and HCA. *Food Res. Int.* **2023**, *164*, 112386. [CrossRef] [PubMed]
87. Goffman, F.D.; Becker, H.C. Genetic variation of tocopherol content in a germplasm collection of *Brassica napus*. L. *Euphytica* **2002**, *125*, 189–196. [CrossRef]
88. Petersom, D.M.; Qureshi, A.A. Genotype and environment effects on tocols of barley and oats. *Cereal Chem.* **1993**, *70*, 157–162.
89. Petersom, D. Oat tocols: Concentration, and stability in oat products and distribution within the kernel. *Cereal Chem.* **1995**, *72*, 21–24.
90. Bustamante-Rangel, M.; Belgado-Zamarreño, M.M.; Sánchez Pérez, A.; Carabias-Martínez, R. Determination of tocopherols and tocotrienols in cereals by pressurized liquid extraction-liquid chromatography-mass spectrometry. *Anal. Chim. Acta* **2007**, *58*, 216–221. [CrossRef] [PubMed]
91. Wagner, K.H.; Kamal-Eldin, A.; Elmadfa, I. $\gamma$-Tocopherol—An underestimated vitamin? *Ann. Nutr. Metabol.* **2004**, *48*, 169–188. [CrossRef] [PubMed]
92. Barrera-Arellano, D.; Ruiz-Méndez, V.; Velasco, J.; Márquez-Ruiz, G.; Dobarganes, C. Loss of tocopherols and formation of degradation compounds at frying temperatures in oils differing in degree of unsaturation and natural antioxidant content. *J. Sci. Food Agric.* **2002**, *82*, 1699–1702. [CrossRef]
93. Stevenson, D.G.; Eller, F.J.; Wang, L.; Jane, J.L.; Wang, T.; Inglett, G.E. Oil and tocopherol content and composition of pumpkin seed oil in 12 cultivars. *J. Agric. Food Chem.* **2007**, *55*, 4005–4013. [CrossRef] [PubMed]
94. Egesel, C.Ö.; Gül, M.K.; Kahrıman, F.; Özer, I.; Türk, F. The effect of nitrogen fertilization on tocopherols in rapeseed genotypes. *Eur. Food Res. Technol.* **2008**, *227*, 871–880. [CrossRef]
95. Hussain, N.; Li, H.; Jiang, Y.; Jabeen, Z.; Shamsi, I.H.; Ali, E.; Jiang, L. Response of seed tocopherols in oilseed rape to nitrogen fertilizer sources and application rates. *J. Zhejiang Univ. Sci. B* **2014**, *15*, 181–193. [CrossRef]
96. Filipek-Mazur, B.; Tabak, M.; Gorczyca, O.; Lisowska, A.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.