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Crambe: Seed Yield and Quality in Response to Nitrogen and Sulfur—A Case Study in Northeastern Poland

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Abstract: The aim of this study was to determine the effect of nitrogen (0, 30, 60, 90, 120 kg ha⁻¹) and sulfur (0, 15, and 30 kg ha⁻¹) fertilization on the morphometric parameters of plants, seed yield components, seed and straw yield, N fertilizer use efficiency (NFUE), and quality of crambe seeds. The experiment had a randomized complete block design, and it was carried out in Bałcyny (northeastern Poland) in 2017–2019. In northeastern Poland, the average seed yields ranged from 0.96 to 1.64–1.82 Mg ha⁻¹ (hulled seeds). Seed yield increased significantly in response to 120 kg N ha⁻¹ and 15 kg S ha⁻¹. The NFUE of crambe decreased by 28% with a rise in N rate. Hulled crambe seeds accumulated 324–394 g kg⁻¹ DM of crude fat, 208–238 g kg⁻¹ DM of total protein, and 118–137 g kg⁻¹ DM of crude fiber. Nitrogen fertilization decreased the crude fat content (by 6%), and it increased the total protein content (by 11%) and the crude fiber content (by 14%) of crambe seeds. Sulfur fertilization increased crude fat content (by 4–5%) without inducing significant differences in the total protein content and the crude fat content of seeds.

Keywords: *Crambe abyssinica*; fertilization; seeds and straw yield; fat and protein; fatty acids; fiber

1. Introduction

The oil from plants of the family *Brassicaceae* is a natural source of erucic acid (EA, C_{22:1}), one of very long chain fatty acids (VLCFAs). In plants, VLCFAs and their derivatives are the precursors of suberin, pollen coat, cuticular waxes, and sphingolipids [1]. Erucic acid has numerous industrial applications; it is used in the production of polymers, polyesters, emulsifiers, detergents, ink, paper, cosmetics, pharmaceuticals, textiles, lubricants, food, and fuel [2]. The worldwide consumption of EA increased from 18 to 35 Tg between 1990 and 2010 [3]. The seeds of rapeseed cultivars (*Brassica napus* var. *oleifera* L.) with a high content of erucic acid and low concentrations of glucosinolates (high erucic acid rape, HEAR), as well as crambe seeds (*Crambe abyssinica* Hochst. ex R.E. Fries), are the most popular “green” sources of EA [2,4]. However, the cultivation of HEAR with other rapeseed cultivars (such as low erucic acid rape, LEAR, for food processing) is difficult due to high levels of gene flow mediated by pollen (cross pollination) and seeds (seed shedding during maturation and harvest, and a long period of secondary dormancy) [5,6]. In LEAR production, the risk of EA contamination from HEAR varieties is difficult to control and requires numerous adjustments, including appropriate crop rotations with a low share of *Brassica* crops, the establishment of buffer zones, and effective control of weeds, in particular of the family *Brassicaceae* [6]. At present, the oil from *C. abyssinica* seeds (synonym: Abyssinian oil) is favored over HEAR oil due to a higher content of EA (50–60% vs. 45–50%)

and the absence of the risk of genetic cross-over with edible oilseed crops [7–10]. It should also be noted that only genetically modified HEAR lines have a similar content of C_{22:1} to *C. abyssinica* [5,11].

Crambe is an annual oilseed crop of the family *Brassicaceae*. The species originated in the warm-temperate region of eastern Africa (it is endemic to Ethiopia) with moderate rainfall [10,12,13]. Crambe had been domesticated in the Mediterranean region, and then it was subsequently adapted to colder and drier regions [10,12]. Large-scale production of *C. abyssinica* probably began in the early 1930s at the Voronez Botanical Station in the former USSR (presently northwestern Russia). In the 1940s, crambe was introduced to the northeastern United States by the Connecticut Agricultural Experiment Station. After World War II, crambe was also introduced to other regions of the USSR as well as to Sweden and Poland [14]. At present, crambe is farmed in several regions of the United States, in tropical and subtropical regions of Africa, Middle East, Central and Western Asia, Europe, and South America [15–18]. According to Von Cossel et al. [19], crambe can be potentially produced on around 52,000 ha of marginal land in the European Union (EU-28), in particular in the Mediterranean mountains, in the northern and southern parts of the Mediterranean region (41%), as well as in northern and central Atlantic Europe, and in the Lusitanian Basin (34%). The crop is least suitable for production in Boreal, Continental, Nemoral and Pannonian climate zones [19].

Crambe abyssinica is a winter crop (southern Mediterranean countries and subtropical regions) and a spring–summer crop (northern Europe and regions with a continental climate) [20]. The species easily adapts to varied environmental conditions, and it can be grown in regions with an average annual temperature of 5.7–16.2 °C, annual rainfall of 350–1200 mm, and soil pH range of 5.0–7.8 [21]. As a result, high seed yields (approximately 3 Mg ha⁻¹) can be achieved in highly diverse climates in Europe [14,16,22–25], South America [26–28], North America [29], Asia [17], and Australia [30]. The oil content of crambe seeds is estimated at 260–399 (hulled seeds) and 429–474 g kg⁻¹ dry matter (DM) (dehulled seeds) [16–18,26,30–39]. The fatty acid profile of Abyssinian oil is dominated by monounsaturated fatty acids (MUFAs) (75–82%), including EA (56–63%). Abyssinian oil contains 12–17% of polyunsaturated fatty acids (PUFAs) and 4–8% of saturated fatty acids (SFAs) [17,18,24,33,34]. Abyssinian oil has also a high content of phytosterols (β -sitosterol, campestanol, and brassicasterol) and γ -tocopherol [18]. Crambe seeds are a rich source of protein (189–265 g kg⁻¹ DM in hulled seeds and 258–312 g kg⁻¹ DM in dehulled seeds) [17,31–33,36,37] with a nutritionally desirable amino acid profile that is similar to that of *B. napus* [31,40]. The crude fiber content of crambe seeds is 96–180 (hulled seeds) and 28–103 g kg⁻¹ DM (dehulled seeds) [17,33,36,41], including around 25–33% of neutral detergent fiber (NDF) [33]. Crambe meal can be processed into animal feed and protein isolates [42]. The protein content of defatted crambe meal can reach 250–350 (hulled seeds) to 371–580 g kg⁻¹ DM (dehulled seeds) [21,42,43]. Crambe seeds contain approximately 72–103 μ mol g⁻¹ of glucosinolates (GLS), with a predominant share (90–97%) of *epi*-progoitrin [31,33], which considerably limits the use of crambe as a protein source in animal diets [17,22,30,33]. Due to relatively high levels of GLS (mostly alkenyl GLS), crambe meal is highly toxic for monogastric animals [44]. The Food and Drug Administration (a federal agency of the United States Department of Health and Human Services) restricted the use of crambe meal in ruminant feeds to 4.2% of the total weight of rations [45].

Crambe is known for its desirable agronomic traits such as a short growing season [24,46], tolerance to drought, and adaptability to poor soils in marginal or semiarid land [20], soil salinity, and heavy metal contamination [47]. The species is naturally resistant to insects [48–50], which could be attributed to the high content of GLS [46] that act as natural pesticides against herbivore predation [51]. The cultivars of *C. abyssinica* have a low resistance to pathogens, including *Sclerotinia sclerotiorum* (Lib) de Bary and fungi of the genus *Alternaria*, regardless of agroecological conditions [14,38,52–54]. Other potential diseases include blackleg (*Leptosphaeria maculans* (Desm.) Ces. and de Not.) and root rot (*Pythium* spp.) [52]. Due to its agronomic traits, crambe can be grown in East-Central Europe, including Poland. In comparison with other parts of Europe, this region is characterized by soils of relatively low quality, low precipitation levels, and limited surface water resources. Crambe is drought-tolerant, which may increase its popularity in East-Central Europe under global warming

conditions. There is a general scarcity of published data on the effects of crop rotation on crambe cultivation. In a study conducted in the Northern Great Plains, crambe was a less suitable preceding crop for durum wheat (*Triticum durum* Desf.) than camelina (*Camelina sativa* (L.) Crantz) and Indian mustard (*Brassica juncea* (L.) Czern.) [55]. Crambe was not effective in reducing the population of soybean cyst nematodes (SCN) in soils, which suggests that this crop species is not suitable for sustainable management of pathogens in large-area soybean farms in SCN-infested regions [56]. However, due to its short growing cycle, the species could be a highly suitable preceding crop for winter cereals in Europe [46]. In Australia and New Zealand, *Brassica* crops are more widely used in rotation and intercropping with rice and wheat [57]. The oil and nonfat seed residues of *C. abyssinica* constitute renewable feedstocks for biofuel and bio-based products in the oleochemical industry [25,38,58].

Brassica crops accumulate large amounts of protein, crude fat, and GLS, and they have a high demand for fertilizers, in particular N. Oils are important plant metabolites with the highest energy density among all carbon reserves [59]. Nitrogen affects the distribution of nutrients to roots and assimilative organs, thus influencing photosynthetic capacity and crop stand productivity [60]. Nitrogen is a part of structural compounds, carriers of energy, and genetic information, as well as compounds that regulate plant metabolism. In *Brassica* crops, the synthesis of nutrients and biologically active compounds is a highly energy-intensive process, which could explain low N fertilizer use efficiency (NFUE). In rapeseed, Indian mustard, camelina, field mustard (*Brassica rapa* L.), white mustard (*Sinapis alba* L.), and Abyssinian mustard (*Brassica carinata* A. Braun), NFUE has been determined in the range of 11.1 to 26.4 kg seed kg⁻¹ N [61–63]. In *B. napus*, the highest yielding *Brassica* crop, NFUE is 27–81% lower than in common wheat (*Triticum aestivum* L.) (26 vs. 33–47 kg seed kg⁻¹ N) [61,64,65]. In *B. napus*, the production of 1 Mg of seeds with the corresponding yield of stems, leaves, and roots requires 50–60 kg N [66]. The remaining *Brassica* crops, including *C. sativa* [62,67,68], *B. juncea* and *B. rapa* canolas, *B. juncea* and *S. alba* mustards [61,69], and *S. alba* canola [69], have an equally high demand for N. In oilseed crops of the family *Brassicaceae*, crude fat content is the most important quality trait which is negatively correlated with total protein content [70,71]. Nitrogen decreases the content of crude fat and increases the total protein content of seeds in *Brassica* crops [68,72,73]. A negative correlation between N fertilization and the oil and protein content of seeds is not observed only when N does not exert yield-forming effects [63].

Brassica oilseed crops need 15–20 kg S to produce 1 Mg⁻¹ seeds and the corresponding straw yield [74]. Sulfur is present in selected amino acids and glutathione, which are responsible for the structure of the protein chain [75]. Compounds containing sulfhydryl groups (–SH) participate in redox reactions [76] and determine the activity of many enzymes. Sulfur is also found in sulfolipids, the structural elements of cell membranes [77]. *Brassicaceae* crops have a high demand for S that participates in the biosynthesis of GLS [78]. All GLS contain S and glucose, but they differ in the structure of aglycone, which determines the compound's properties [79]. The effect of S fertilization on the metabolism of *Brassica* plants, including the content of essential nutrients, varies depending on SO₄²⁻ levels in soil, atmospheric deposition of S, the biological activity of soil which affects the transformation rates of S, and agronomic factors [80]. In recent years, S has emerged as an important fertilizer due to the progressive depletion of S from soils, increasing production of *Brassica* crops in agricultural ecosystems, and a significant decrease in annual SO₂ deposition in soils [81]. In Poland, the annual SO₂ emissions to ambient air have decreased nearly five-fold (2.53 vs. 0.56 million Mg) in the past 27 years (1990–2017) [82]. In crops of the family *Brassicaceae*, S fertilizers not only increase yields, but also influence the quality of agricultural products, including oil, fat-free seed residues, and harvest residues [81,83–85]. Sulfur fertilization is much more likely to affect total protein concentration than crude fat concentration in the seeds of *Brassica* oilseed crops [86] because S actively participates in the synthesis of major S-containing amino acids (cysteine and methionine) [87].

The aim of this study was to determine the effect of N and S fertilization on plant parameters (plant height, shoot diameter at the base, number of productive branches), yield (seed yield, yield components, straw yield, harvest index), and the processing suitability of crambe seeds as

a potential feedstock for bio-based products in the oleochemical industry (content of crude fat, total protein, crude fiber, fatty acids, acid detergent fiber (ADF) and NDF) in northeastern Poland.

2. Materials and Methods

2.1. Field Experiment

Crambe (*Crambe abyssinica* Hochst. ex R.E. Fries) was grown in the Agricultural Experiment Station in Bałcyny (53°35'46.4" N, 19°51'19.5" E, elevation 137 m) in northeastern (NE) Poland in 2017–2019. The station is part of the University of Warmia and Mazury in Olsztyn. The experimental variables were (i) N rate (kg ha⁻¹) 0, 30, 60, 90, 120 and (ii) S rate (kg ha⁻¹) 0, 15, 30. A single rate of N was applied immediately before sowing at up to 90 kg ha⁻¹. Higher N rates (120 kg ha⁻¹) were split into two doses: 90 kg N ha⁻¹ immediately before sowing and 30 kg N ha⁻¹ in BBCH stages 22–23 (identification key for growth stages [88]). Nitrogen was applied as ammonium nitrate (34% N). Sulfur was applied as potassium sulfate (18% S, 50% K₂O) immediately before sowing.

The experiment had a randomized complete block design (RCB) with three replications. Plot size was 15 m² (10 by 1.5 m). In each year of the study, the preceding crop was spring wheat (*Triticum aestivum* L.). The applied tillage treatments were skimming, winter plowing, and soil loosening before sowing. Crambe cv. Borowski was sown at the beginning of April (9–11 April) with a plot seeder at 200 pure live seeds m⁻², with a spacing of 19 cm, to a depth of 1.5–2.0 cm. Directly before sowing, phosphorus (enriched superphosphate, 40% P₂O₅) was applied at 40 kg ha⁻¹ P₂O₅, and potassium (potassium sulfate, 50% K₂O, and/or potash salt, 60% K₂O) was applied at 100 kg ha⁻¹ K₂O. Weeds were controlled with metazachlor, which was applied at 1000 g ha⁻¹ immediately after sowing. Pesticide (6 g ha⁻¹ lambda-cyhalothrin) was applied at the beginning of inflorescence emergence (50 BBCH). Crambe was harvested at physiological maturity (89 BBCH) using a small-plot harvester (5–29 August).

The experiment was established on Haplic Luvisol originating from boulder clay [89]. The chemical properties of the soil are presented in the Table 1.

Table 1. Chemical properties of the analyzed soil.

Years	pH ^a	C _{org} (g kg ⁻¹) ^b	Available Macronutrients (mg kg ⁻¹) ^c			
			P	K	Mg	SO ₄ ²⁻
2017	6.2	1.10	42.1	157.7	72.0	12.5
2018	6.0	1.25	37.5	145.2	81.0	11.7
2019	6.0	1.05	59.3	108.1	60.0	13.3

^a digital pH meter with temperature compensation (20 °C) in deionized water and 1 mol dm⁻³ KCl, at a 5:1 ratio.

^b modified Kurmies method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan). ^c P—vanadium molybdate yellow colorimetric method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan); K—atomic emission spectrometry (AES) (Flame Photometers, BWB Technologies Ltd., Newbury, UK); Mg—atomic absorption spectrophotometry (AAS) (AAS1N, Carl Zeiss Jena, Germany); and SO₄²⁻—nephelometry method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan).

2.2. Plant Materials

The biomass yield of crambe (hulled seeds and straw) from each plot was determined by weight after threshing and expressed in DM per hectare, taking into account the moisture content of samples after oven-drying at 105 °C. The main morphometric parameters (plant height, shoot diameter at the base, number of productive branches) and yield components (plants m⁻² and hulled seeds plant⁻¹) were determined immediately before harvest (89 BBCH). Plants were counted (plant m⁻² and morphometric parameters) along a 1-m-long section of each of the two middle rows [90]. The number of hulled seeds plant⁻¹ was calculated as the ratio between hulled seed yield and hulled seed weight [24]. Thousand hulled seed weight (TSW) was determined after harvest and expressed on a DM basis,

taking into account the moisture content of samples after oven-drying at 105 °C. The harvest index (HI) was calculated using Equation (1):

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

Nitrogen fertilizer use efficiency (NFUE) was calculated with Equation (2) [61]:

$$NFUE = \frac{\text{Hulled seed yield in N treatments (kg ha}^{-1}\text{)} - \text{Hulled seed yield without N (kg ha}^{-1}\text{)}}{\text{N rate (kg ha}^{-1}\text{)}} \quad (2)$$

Hulled seed samples were scanned in the NIR Systems 6500 monochromator (FOSS NIR Systems Inc., Laurel, MD, USA) equipped with a reflectance module. Intact seeds (approximately 5 g) were placed in a standard ring cup and scanned. The content of total protein, crude fat, crude fiber, ADF, and NDF in crambe seeds, and the fatty acid composition of Abyssinian oil, were determined according to the procedures described by Jankowski et al. [68].

2.3. Statistical Analysis

Data were analyzed in the general linear mixed model in Statistica software [91] with N and S fertilizers as the fixed effects, and the growing season (Y) and replications nested within years as the random effects. Post hoc multiple comparisons were performed with the use of Tukey's test (HSD) in subsequent stages of statistical analyses. Data were regarded as statistically significant at $\alpha = 0.05$. The results of the *F*-test for fixed effects in ANOVA are presented in Table 2.

Table 2. *F*-test statistics in ANOVA.

Trait	Y	N	S	Y × N	Y × S	N × S	Y × N × S
Plant height (cm)	459.71 **	8.01 **	2.77 ns	1.7 ns	2.47 ns	0.54 ns	0.34 ns
Shoot diameter at base (mm)	59.91 **	25.07 **	1.86 ns	4.09 **	0.56 ns	1.66 ns	0.62 ns
Number of branches	47.53 **	15.43 **	0.79 ns	1.28 ns	0.60 ns	0.26 ns	0.07 ns
Plants m ⁻²	151.17 **	4.23 **	0.56 ns	1.28 ns	0.79 ns	0.14 ns	0.13 ns
Seeds plant ⁻¹	49.17 **	12.59 **	2.25 ns	5.47 **	0.21 ns	0.36 ns	0.37 ns
TSW (g)	22.57 **	1.16 ns	16.27 **	4.90 **	2.13 ns	0.95 ns	0.30 ns
Seed yield (Mg ha ⁻¹)	273.58 **	26.20 **	9.17 **	4.47 **	0.53 ns	0.74 ns	0.31 ns
NFUE (kg seed kg ⁻¹ N)	7.91 **	3.61 ns	0.31 ns	1.65 ns	0.29 ns	0.79 ns	0.30 ns
Straw yield (Mg ha ⁻¹)	313.05 **	10.51 **	5.28 **	1.13 ns	0.51 ns	0.59 ns	0.55 ns
Harvest index	79.53 **	1.57 ns	1.36 ns	2.42 *	0.62 ns	0.64 ns	0.29 ns
Crude fat content (g kg ⁻¹ DM)	111.64 **	4.14 **	5.00 **	1.24 ns	4.05 **	1.23 ns	0.84 ns
C ₁₆ (%)	3.30 *	3.56 **	0.69 ns	1.77 ns	0.21 ns	0.86 ns	1.42 ns
C ₁₈ (%)	0.57 ns	0.31 ns	0.85 ns	1.21 ns	0.37 ns	0.35 ns	0.52 ns
C _{18:1} (%)	7.17 **	0.05 ns	0.06 ns	0.16 ns	0.04 ns	0.02 ns	0.05 ns
C _{18:2} (%)	135.94 **	4.50 *	2.93 *	2.03 ns	1.27 ns	1.09 ns	1.09 ns
C _{18:3} (%)	6.44 **	2.61 *	0.31 ns	0.61 ns	1.10 ns	0.92 ns	0.68 ns
C _{20:1} (%)	56.90 **	0.06 ns	0.26 ns	0.23 ns	0.28 ns	0.05 ns	0.22 ns
C _{22:1} (%)	20.71 **	0.07 ns	0.10 ns	0.20 ns	0.14 ns	0.20 ns	0.18 ns
SFAs (%)	2.98 ns	1.63 ns	0.38 ns	0.50 ns	0.27 ns	0.97 ns	1.72 ns
MUFAs (%)	6.83 **	0.15 ns	0.01 ns	0.33 ns	0.17 ns	0.34 ns	0.20 ns
PUFAs (%)	6.52 **	0.03 ns	0.01 ns	0.10 ns	0.12 ns	0.22 ns	0.07 ns
Total protein content (g kg ⁻¹ DM)	44.59 **	9.25 **	2.97 ns	6.64 **	0.66 ns	0.85 ns	0.70 ns
Crude fiber content (g kg ⁻¹ DM)	11.68 **	3.78 **	1.06 ns	0.29 ns	1.55 ns	1.27 ns	0.79 ns
NDF (%)	55.11 **	4.95 **	0.48 ns	1.57 ns	0.23 ns	0.60 ns	0.48 ns
ADF (%)	0.00 ns	1.78 ns	0.10 ns	1.01 ns	0.28 ns	0.62 ns	0.34 ns

* significant $p < 0.05$; ** significant $p < 0.01$; ns—not significant. Y—growing season; N—nitrogen fertilization; S—sulfur fertilization; TSW—1000-seed weight; NFUE—nitrogen fertilizer use efficiency; C₁₆—palmitic acid; C₁₈—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; SFA—saturated fatty acids; MUFA—monounsaturated fatty acids; PUFA—polyunsaturated fatty acids; ADF—acid detergent fiber; NDF—neutral detergent fiber.

3. Results

3.1. Weather Condition

The growing seasons (April–August) during the field experiment differed in temperature and precipitation levels (Figure 1). In the first growing season, the average daily temperature approximated the long-term average (1981–2015). In the second growing season, the average daily temperature exceeded the long-term average. In the third growing season, the average daily temperature was similar to the long-term average, excluding June when this parameter exceeded the long-term average. Total rainfall in March–August was 264 mm in 2017, 331 mm in 2018, and 371 mm in 2019. At the experimental site, the average long-term precipitation during the growing season over the last 37 years (in 1981–2015) reached 342 mm. The first growing season was characterized by low total precipitation due to rainfall deficiency in May, July, and August (59, 65, and 31% of the long-term average, respectively). In the second growing season, rainfall levels approximated the long-term average (1981–2015). In the third year of the study, the wet months of May and June (with precipitation levels 66% and 28% higher than the long-term average, respectively) contributed to above-average precipitation levels during the entire growing season (March–August) (Figure 1).

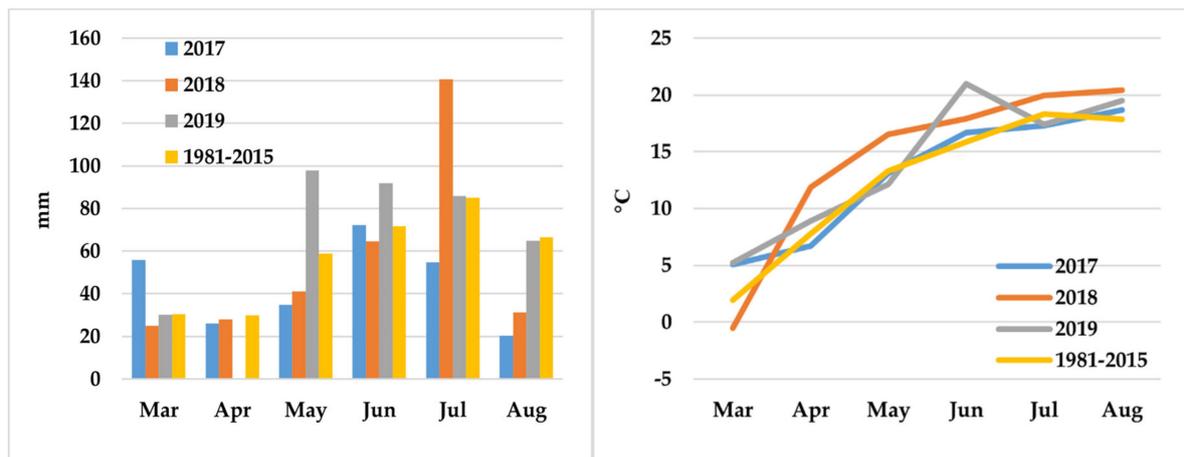


Figure 1. Total monthly rainfall (mm) and average monthly temperature (°C) during the growing season of crambe in 2017–2019 and the long-term average (1981–2015) at the experimental site.

3.2. Plant Height

Crambe plants produced shoots with a length of 65–103 cm, base diameter of 5–6 mm, and 7–8 productive branches (Table 3). The vegetative growth rate of *C. abyssinica* was highest in the third year of the study (Table 3) when precipitation levels exceeded the long-term average in May and June (Figure 1).

Table 3. Selected morphometric properties of crambe plants.

Parameter	Plant Height (cm)	Shoot Diameter at Base (mm)	Number of Branches
Year			
2017	65.0 ^c	5.4 ^b	6.8 ^c
2018	69.2 ^b	5.4 ^b	7.4 ^b
2019	103.4 ^a	6.4 ^a	8.5 ^a
Nitrogen rate (kg ha ⁻¹), across years			
0	73.4 ^b	5.0 ^c	6.5 ^c
30	79.3 ^a	5.5 ^b	7.6 ^b
60	79.2 ^a	6.0 ^{ab}	7.7 ^{ab}
90	81.2 ^a	6.0 ^a	7.8 ^{ab}
120	83.0 ^a	6.3 ^a	8.2 ^a

Table 3. Cont.

Parameter	Plant Height (cm)	Shoot Diameter at Base (mm)	Number of Branches
Sulfur rate (kg ha ⁻¹), across years			
0	77.4	5.6	7.4
15	80.6	5.7	7.6
30	79.5	5.9	7.7

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of superscript letters indicates that the main effects or interactions were not statistically significant.

Nitrogen fertilization stimulated the vegetative growth of crambe. Crambe plants fertilized with N produced significantly taller (by 10%) and thicker shoots (by 20%) with more productive branches (by 26%) relative to the control treatment (without N fertilization). Nitrogen stimulated the vegetative growth of *C. abyssinica* up to the rate of 30 taller shoots, 90 thicker shoots, and 120 kg ha⁻¹ higher number of productive branches. Nitrogen had no beneficial influence on shoot thickness except in the dry year of 2017, in particular during seed setting and filling (July and August) (Figure 2). Sulfur fertilization did not induce significant differences in the vegetative growth rate of *C. abyssinica* (Table 3).

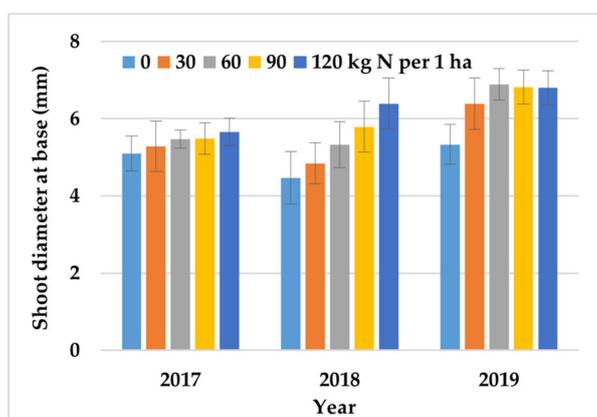


Figure 2. The effect of N fertilization on the shoot diameter of crambe plants across growing seasons (2017–2019). Error bars represent the standard deviation.

3.3. Yield Components

The density of *C. abyssinica* stands before harvest ranged from 129 (2017) to 162–166 (2018, 2019) plants m⁻². In NE Poland, crambe produced 94 do 131 seeds plant⁻¹ with TSW (hulled seeds) of 8.0 to 8.7 g (Table 4). Yield components were most favorable in the third year of the study that was characterized by above-average precipitation in the growing season. Yield components were least expressed in the dry year of 2017 (first year of the experiment). Water-stressed plants were characterized by lower density (by 21%) and set significantly fewer seeds (by 28%) with lower TSW (by 8%) (Table 4).

Table 4. Yield components and biomass yield of crambe.

Parameter	Plants m ⁻²	Seeds plant ⁻¹	TSW (g)	Seed Yield (Mg ha ⁻¹)	NFUE (kg seeds kg ⁻¹ N)	Straw Yield (Mg ha ⁻¹)	Harvest Index
Year							
2017	129 ^b	94.0 ^c	8.0 ^c	0.96 ^c	2.09 ^b	1.24 ^c	0.43 ^b
2018	166 ^a	121.0 ^b	8.3 ^b	1.64 ^b	5.63 ^a	1.80 ^b	0.48 ^a
2019	162 ^a	131.1 ^a	8.7 ^a	1.82 ^a	5.89 ^a	3.40 ^a	0.35 ^c
Nitrogen rate (kg ha ⁻¹), across years							
0	145 ^b	99.6 ^c	8.4	1.22 ^d	—	1.90 ^c	0.41
30	154 ^a	105.7 ^{bc}	8.3	1.38 ^c	5.27	1.88 ^c	0.44
60	153 ^a	117.7 ^{ab}	8.3	1.51 ^{bc}	4.94	2.15 ^{bc}	0.42
90	155 ^a	124.1 ^a	8.2	1.59 ^{ab}	4.14	2.28 ^{ab}	0.42
120	155 ^a	129.6 ^a	8.4	1.67 ^a	3.80	2.52 ^a	0.42

Table 4. Cont.

Parameter	Plants m ⁻²	Seeds plant ⁻¹	TSW (g)	Seed Yield (Mg ha ⁻¹)	NFUE (kg seeds kg ⁻¹ N)	Straw Yield (Mg ha ⁻¹)	Harvest Index
Sulfur rate (kg ha ⁻¹), across years							
0	151	111.1	8.1 ^b	1.38 ^b	4.62	2.02 ^b	0.42
15	153	119.3	8.1 ^b	1.50 ^a	4.08	2.11 ^{ab}	0.43
30	152	115.6	8.7 ^a	1.54 ^a	4.91	2.31 ^a	0.41

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of superscript letters indicates that the main effects or interactions were not statistically significant. TSW—1000-seed weight; NFUE—nitrogen fertilizer use efficiency.

Nitrogen fertilization increased plant density before harvest (by 6%) and the number of seeds plant⁻¹ (by 25%) (Table 4). Nitrogen exerted a positive effect on plant density and the number of seeds plant⁻¹, up to the rate of 30 and 90 kg ha⁻¹, respectively. An interaction was found between N fertilization and weather conditions for the number of seeds plant⁻¹ and TSW (Table 2). In the growing season characterized by high yields (high precipitation in the third year of the experiment), an increase in N rate to 120 kg ha⁻¹ led to a 1.7-fold increase in the number of seeds plant⁻¹ accompanied by a 12% decrease in TSW (Figure 3). In the year with average precipitation (2018), the number of seeds plant⁻¹ increased by 16% in response to the N rate of up to 60 kg N ha⁻¹. In the driest year of 2017, N fertilization had no significant effect on the number of seeds plant⁻¹ (Figure 3).

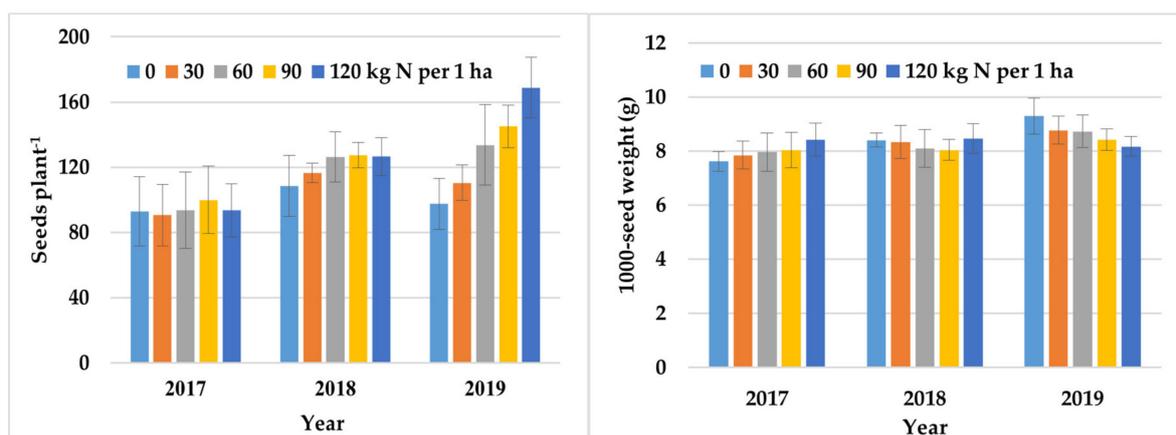


Figure 3. The effect of N fertilization on the number of seeds plant⁻¹ and 1000-seed weight of crambe across growing seasons (2017–2019). Error bars represent the standard deviation.

Thousand-seed weight increased by 6% in response to the S fertilization rate of up to 30 kg ha⁻¹ (Table 4), regardless of agroecological conditions or N rate (Table 2). The remaining yield components (plants m⁻² and seeds plant⁻¹) were not significantly affected by S fertilization (Table 2).

3.4. Biomass Yield and Harvest Index

In NE Poland, the average seed yield of crambe ranged from 0.96 to 1.64–1.82 Mg ha⁻¹ (hulled seeds). Nitrogen rates up to 120 kg ha⁻¹ contributed to a significant increase in seed yield (by 0.45 Mg ha⁻¹), mainly due to the beneficial influence of N on the number of plants m⁻² and seeds plant⁻¹ (Table 4). Nitrogen rates up to 120 kg ha⁻¹ improved yields (Figure 4) in years with average and above-average precipitation during the growing season of *C. abyssinica* (2018, 2019). In the year with below-average precipitation (2017), N rates of 30–120 kg ha⁻¹ were not productive (Figure 4). Sulfur rates up to 15 kg ha⁻¹ induced a significant increase in seed yield (by 0.12 Mg ha⁻¹, i.e., 9%) relative to the unfertilized control (Table 4), regardless of agroecological conditions or N rate (Table 2).

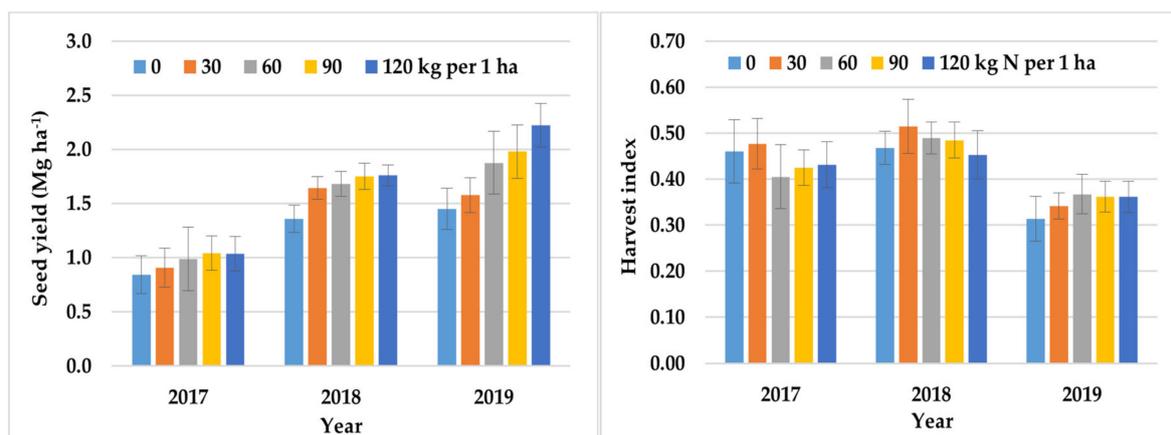


Figure 4. The effect of N fertilization on crambe seed yields and harvest index across growing seasons (2017–2019). Error bars represent the standard deviation.

The NFUE of crambe ranged from 2.1 (2017) to 5.6–5.9 kg of hulled seeds kg⁻¹ N (2018, 2019). An increase in N rate from 30 to 120 kg N ha⁻¹ decreased NFUE by 28% on average (Table 4), regardless of agroecological conditions (Table 2). It should be noted that S fertilization increased the efficiency of N rates of ≥ 30 kg ha⁻¹ by 29–39% (60 kg N ha⁻¹), 23–31% (90 kg N ha⁻¹), and 22% (120 kg N ha⁻¹) (Figure 5). In treatments with low N fertilization levels (30 kg ha⁻¹), the application of S caused a 1.7- to 2.1-fold decrease in NFUE (Figure 5).

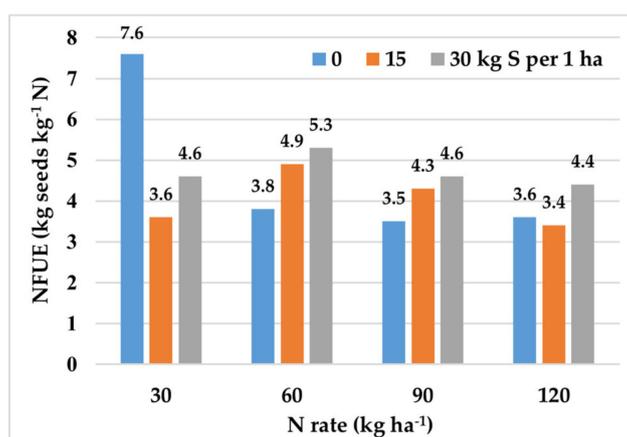


Figure 5. Nitrogen fertilizer use efficiency in treatments with different S fertilization rates (across years).

Straw yield ranged from 1.24–1.80 (2017, 2018) to 3.40 Mg ha⁻¹ DM (2019) (Table 4). This parameter increased significantly up to the N rate of 120 kg N ha⁻¹ (33%) and the S rate of 30 S ha⁻¹ (14%) (Table 4), regardless of agroecological conditions (Table 2).

The content of *C. abyssinica* seeds in total harvested biomass (hulled seeds + straw) ranged from 35 to 48% (Table 4). Nitrogen rates of ≥ 60 kg ha⁻¹ had a negative impact on the ratio of seeds to straw (the harvest index decreased from 0.49–0.41 to 0.31–0.37) in years with average and above-average precipitation (2018 and 2019, respectively) (Figure 1). In the year with below-average precipitation (2017), N fertilization had no significant effect on the value of HI (Figure 4). The content of seeds in the total harvested biomass of *C. abyssinica* was not significantly affected by S fertilization levels (Table 2).

3.5. Quality of Seeds and Oil

Hulled crambe seeds contained 324–394 g kg⁻¹ DM of crude fat and 208–238 g kg⁻¹ DM of total protein. Crude fat and total protein content were highest in the year with average precipitation (2018). In years with below-average (2017) or above-average (2019) precipitation, crude fat and total protein

content was 15–18% and 10–12% lower, respectively. Nitrogen fertilization decreased the crude fat content of *C. abyssinica* seeds by 6% and increased total protein content by 11% (Table 5). Nitrogen rates up to 60 kg ha⁻¹ decreased the synthesis of crude fat in seeds (Table 5), regardless of agroecological conditions (Table 2). On average, the total protein content of seeds increased up to the N rate of 90 kg N ha⁻¹ throughout the entire study (Table 5). However, total protein content was strongly influenced by the interaction between N rate and weather conditions. In the dry year of 2017, the total protein content of crambe seeds increased up to the N rate of 120 kg ha⁻¹. In years with average (2018) and above-average precipitation (2019), total protein content increased up to the N rates of 90 and 30 kg ha⁻¹, respectively (Figure 6). Sulfur rates up to 30 kg ha⁻¹ contributed to a 4–5% increase in the crude fat content of crambe seeds (Table 5), excluding in the year with above-average precipitation (2019) when the greatest increase in crude fat content was observed already in response to the S rate of 15 kg ha⁻¹ (Figure 7). Sulfur fertilization had no significant effect on the total protein content of seeds, regardless of N rate or weather conditions (Table 2).

Table 5. Nutrient content of crambe seeds.

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					
2017	324.1 ^b	214.8 ^b	129.2 ^a	32.5	45.0 ^a
2018	393.6 ^a	237.6 ^a	137.4 ^a	32.5	34.4 ^b
2019	335.5 ^b	208.2 ^b	117.6 ^b	32.6	44.2 ^a
Nitrogen rate (kg ha ⁻¹), across years					
0	367.0 ^a	206.5 ^c	118.2 ^b	33.6	38.1 ^c
30	351.4 ^{ab}	215.9 ^{bc}	123.1 ^{ab}	33.5	40.0 ^{bc}
60	346.6 ^b	225.1 ^{ab}	129.7 ^{ab}	32.4	41.4 ^{abc}
90	345.7 ^b	229.2 ^a	134.8 ^a	32.6	42.2 ^{bc}
120	344.6 ^b	224.2 ^{ab}	134.5 ^a	30.7	44.2 ^a
Sulfur rate (kg ha ⁻¹), across years					
0	344.0 ^c	215.6	125.0	32.6	40.8
15	349.6 ^{ab}	222.1	131.0	32.7	41.8
30	359.6 ^a	222.8	128.3	32.3	41.0

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of superscript letters indicates that the main effects or interactions were not statistically significant.

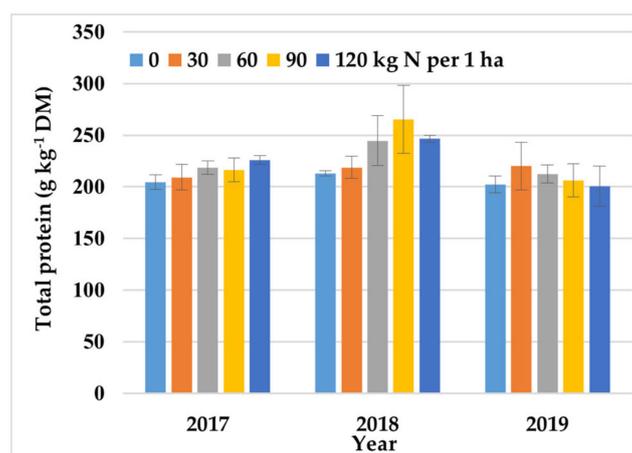


Figure 6. The effect of N fertilization on the total protein content of crambe seeds across growing seasons (2017–2019). Error bars represent the standard deviation.

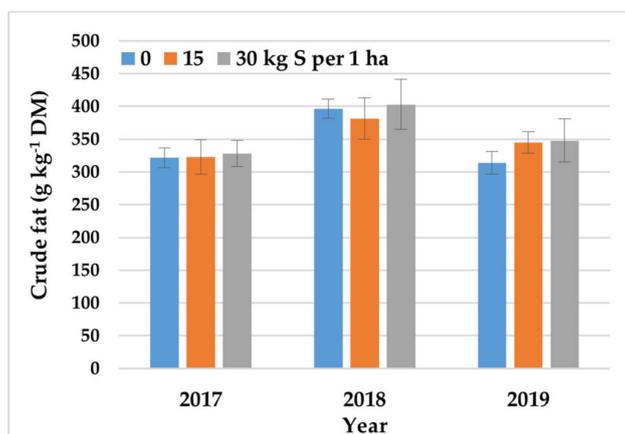


Figure 7. The effect of S fertilization on the crude fat content of crambe seeds across growing seasons (2017–2019). Error bars represent the standard deviation.

The crude fiber content of crambe seeds ranged from 118 to 137 g kg⁻¹ DM, and the proportions of ADF and NDF were determined at 33% and 43–45%, respectively (Table 5). The crude fiber content of seeds was significantly lower (by 9–14%) in the year with above-average precipitation (2019) in the treatment without N fertilization (118 g kg⁻¹ DM). Nitrogen rates up to 90 kg ha⁻¹ increased the content of crude fiber and NDF by 14% and 4%, respectively. Sulfur fertilization had no significant effect on the crude fiber content of seeds or the proportions of NDF and ADF (Table 2).

Erucic acid was the predominant component of Abyssinian oil, and it accounted for 57–65% of total fatty acids (Table 6). Abyssinian oil also contained considerable amounts of oleic acid (15–19%) and linoleic acid (9–11%) (Table 6). Abyssinian oil was most abundant in MUFAs which accounted for 79–82% of all fatty acids. Nitrogen fertilization increased the content of linoleic acid (from 9.2% to 9.8%) and decreased the content of linolenic acid (from 7.2% to 6.6%) (Table 6). The proportions of SFAs, PUFAs, and MUFAs in Abyssinian oil were not significantly differentiated by N rate (Table 2). Sulfur fertilization significantly decreased the content of linoleic acid in Abyssinian oil (Table 6), but had no effect on the concentrations of the remaining FAs or the proportions of SFAs, MUFAs, or PUFAs (Table 2).

Table 6. Fatty acid composition of crambe oil (%).

Parameter	C ₁₆	C ₁₈	C _{18:1}	C _{18:2}	C _{18:3}	C _{20:1}	C _{22:1}	SFAs	MUFAs	PUFAs
Year										
2017	2.0 ^a	0.7	18.7 ^a	10.8 ^a	7.2	3.7 ^a	56.8 ^b	2.7	79.3 ^b	18.0 ^a
2018	1.9 ^{ab}	0.7	17.7 ^a	8.6 ^b	6.7	2.1 ^b	62.3 ^a	2.6	82.0 ^a	15.3 ^b
2019	1.7 ^b	0.7	14.7 ^b	9.5 ^b	6.7	1.4 ^c	65.0 ^a	2.4	81.4 ^a	16.2 ^b
Nitrogen rate (kg ha ⁻¹), across years										
0	1.6 ^b	0.7	17.3	9.2 ^b	7.2 ^a	2.4	61.6	2.3 ^b	81.3	16.4
30	1.8 ^{ab}	0.6	17.3	9.6 ^{ab}	7.0 ^{ab}	2.4	61.3	2.4 ^{ab}	81.0	16.6
60	2.1 ^a	0.7	17.2	9.8 ^a	6.9 ^{ab}	2.4	60.9	2.7 ^a	80.6	16.6
90	2.1 ^a	0.7	16.9	9.8 ^a	6.7 ^{ab}	2.5	61.3	2.8 ^a	80.7	16.5
120	2.02 ^a	0.7	16.9	9.7 ^{ab}	6.6 ^b	2.3	61.7	2.7 ^{ab}	81.0	16.3
Sulfur rate (kg ha ⁻¹), across years										
0	1.8	0.7	17.1	9.6 ^{ab}	6.9	2.5	61.3	2.5	80.9	16.6
15	1.9	0.7	17.3	9.7 ^a	6.8	2.4	61.1	2.6	80.8	16.5
30	1.9	0.6	16.9	9.5 ^b	6.9	2.3	61.7	2.6	81.0	16.4

Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey's test. The absence of superscript letters indicates that the main effects or interactions were not statistically significant. C₁₆—palmitic acid; C₁₈—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; SFA—saturated fatty acids; MUFA—monounsaturated fatty acids; PUFA—polyunsaturated fatty acids.

4. Discussion

4.1. Biomass Yield

In Europe, crambe yields range from 1 to 1.6 Mg ha⁻¹ in regions with a subarctic climate [21], from 2 to 3 Mg ha⁻¹ in humid continental and oceanic climates [14,22,25,92], and can reach 3–4 Mg ha⁻¹ in the Mediterranean climate [16,23]. In NE Poland with a humid continental climate (Köppen classification), crambe yields were determined at 0.9–1.8 Mg ha⁻¹ [38] (this study, Table 4) to 3.1 Mg ha⁻¹ [25]. In the group of *Brassica* crops best suited for cultivation in Poland, *C. abyssinica* is characterized by high yield variation (65%) next to camelina (74%) and garden cress (*Lepidium sativum* L.) (62%) [35]. Crambe yields reach 1.7–2.1 Mg ha⁻¹ in the humid subtropical climate of southern Brazil [26–28]. In the hot desert climate of Arizona, USA, crambe seed yields were determined at 1.7–2.9 Mg ha⁻¹ [29]. Crambe seed yields range from 1.3 to 3.1 Mg ha⁻¹ in the semiarid climate of Western Australia [30] (Table 7).

The harvest index of *C. abyssinica* was determined at 0.29–0.37 by Fontana et al. [16] and Stolarski et al. [38], and it ranged from 0.39 to 0.48 in the work of Stolarski et al. [25] and in the present study (Table 4).

In the production of *C. abyssinica*, all agronomic requirements for the species, as well as adequate soil management and plant nutrition requirements, have to be met to achieve high and stable seed yields [54]. Detailed fertilization recommendations for the species discussed are not available in the literature, and the effect of fertilization on the development of crambe plants and seed yields is ambiguous in the existing research [25,26,93].

Crambe has similar soil fertility requirements to mustards and rapeseed [54]. According to Endres and Schatz [52], around 50 kg of N is required to produce 1 Mg of seeds and the corresponding amount of straw. In Brazil, crambe seed yields peaked in response to N rates of 40 [94] to 60–90 kg ha⁻¹ [27,93]. In a study conducted by Cihacek and Gonzales [95] in North Dakota (northern USA), seed yield increased up to the N rate of 100 kg ha⁻¹. In the current study, seed yields continued to increase up to the N rate of 120 kg ha⁻¹, mainly due to an increase in the number of plants m⁻² and seeds plant⁻¹. In another study conducted in NE Poland, crambe seed yields increased up to the N rate of 80 kg ha⁻¹ due to an increase in the number of seeds plant⁻¹ and TSW [96]. Stolarski et al. [25] reported high and stable crambe yields (2.1 Mg ha⁻¹) in NE Poland in treatments without N fertilization where winter wheat was the preceding crop. In the present study, N fertilization did not increase the seed yield of *C. abyssinica* in the year with low precipitation.

In this study, the NFUE of crambe ranged from 2.1 to 5.9 kg seeds kg⁻¹ N, subject to precipitation levels. As expected, *C. abyssinica* yields decreased with a rise in N rate (from 5.3 to 3.8 kg hulled seeds kg⁻¹ N). Similar trends were reported in studies of *C. sativa* [63,68] and other *Brassica* crops (*B. juncea*, *B. napus* and *B. rapa* canolas, and *B. juncea* and *S. alba* mustards) [61].

Oilseed crops of the family *Brassicaceae* have high S requirements [81]. In soils with moderate levels of S (10–35 mg SO₄²⁻ kg⁻¹ soil [97], seed yields peaked in response to 20–30 kg S ha⁻¹ in *B. juncea* (traditional and canola type cultivars), *C. sativa*, and *C. abyssinica* [68,81,84,85,98]; 40 kg S ha⁻¹ in *B. napus* (spring cultivars) and *S. alba*; and 40 to 80 kg S ha⁻¹ in *B. napus* (winter cultivars) [81,83,99]. The current study was conducted on Haplic Luvisol originating from boulder clay with moderate SO₄²⁻ levels, and crambe yields increased up to the S rate of 15 kg ha⁻¹ (5%), mainly due to the beneficial influence of S on TSW and, to a lesser degree, on the number of seeds plant⁻¹. Szczebiot [96] also reported a 5% increase in crambe seed yields in response to the S rate of 25 kg ha⁻¹ in NE Poland.

Sulfur fertilization plays a key role in the production of *Brassica* crops because it directly affects seed yield and yield components, and indirectly increases the efficiency of N fertilization [68,100,101]. In the present study, S fertilization increased NFUE when N was applied at rates higher than 30 kg N ha⁻¹, by 29–39% (60 kg N ha⁻¹), 23–31% (90 kg N ha⁻¹), and 22% (120 kg N ha⁻¹). When N was applied at 30 kg ha⁻¹, S fertilization caused a 1.7- to 2.1-fold decrease in NFUE. Similar trends were reported in other studies, where NFUE increased in response to S fertilization, particularly at higher N rates, in the production of *C. sativa* [68,102–104], *B. juncea* and *B. rapa* [86], and *S. alba* [105].

Table 7. Crambe seed yield, seed protein, and oil content, as reported in the literature reviewed.

Traits	Units	Crop	Value Range	Region	Reference
Yield	Mg ha ⁻¹	<i>C. abyssinica</i>	1.0–1.6	Europe, subarctic	[21]
			2.0–3.0	Europe, humid continental	[14,22,25,92]
			3.0–4.0	Europe, Mediterranean	[16,23]
			1.7–2.1	Brazil (humid subtropical)	[26–28]
			1.7–2.9	USA, hot desert (Arizona)	[29]
			1.3–3.1	Australia (semiarid)	[30]
Yield variation	%	<i>C. abyssinica</i>	65	Poland (humid continental)	[35]
			62	Poland	[35]
			74	Poland	[35]
Seed protein	g kg ⁻¹ DM	<i>C. abyssinica</i>	189–218	European Russian, Poland	[36,37]
			208–238	Poland	this study
Seed fat	g kg ⁻¹ DM	<i>C. abyssinica</i>	360–300	Russia	[37]
			298–379	Poland	[34–36,38], this study
			260–340	Portugal (Mediterranean climate)	[39]
			345–365	Brazil (humid subtropical)	[26]

4.2. Quality of Seeds and Oil

The seeds produced by plants of the genus *Crambe* (L.) have numerous applications in food processing, feed, oleochemical, and petrochemical industries [106]. The species differ in oil content and the quantitative and qualitative composition of fatty acids. The oil of *C. cordifolia* (Steven) and *C. maritima* (L.) is a valuable source of oleic acid (28–31%). Oleic acid content is twice lower in Abyssinian oil. The seeds of *C. steveniana* (Rupr) and *C. tatarica* (Sebeok) contain three times more linoleic acid (25–26%) than the seeds of *C. abyssinica*. Eicosanoic acid is present in the seeds of most *Crambe* species (15–16%), excluding *C. abyssinica*. *Crambe pinnatifida* (R. Br) is the most abundant source of linolenic acid (9–10%). Erucic acid concentrations are highest in Abyssinian oil (58%), and they are more than twice lower in the remaining species of the genus *Crambe* [107]. The genus *Crambe* is composed of more than 30 species [108], and *C. abyssinica* has the highest economic importance [12]. Hulled seeds of *C. abyssinica* cultivars grown in Russia (Polet, Demetra, VIR 1, and VIR 2) contain 360–399 g kg⁻¹ of crude fat [37]. The crude fat content of hulled seeds in crambe cultivars grown in Poland (cvs. Borowski, Indy, Prophet, and Galactica) ranges from 298 to 379 g kg⁻¹ DM [34–36,38] (this study, Table 5). The crude fat content of crambe seeds (cv. FMS Brillhante) grown in Portugal (Mediterranean climate) was determined at 260–340 g kg⁻¹ DM [39]. The crude fat content of hulled crambe seeds harvested in the humid subtropical climates of southeastern Brazil (cv. FMS Brillhante) and southwestern China (cv. Meyer) ranged from 345 to 364 g kg⁻¹ DM hulled seeds [17,26] (Table 7). Abyssinian oil is most abundant in erucic acid (52–65%), followed by oleic acid (15–19%), linoleic acid (9–11%), and linolenic acid (4–7%) [24,33,34] (this study, Table 6). The content of SFAs in Abyssinian oil does not exceed 9% [18,24,33,34] (this study, Table 6). The qualitative and quantitative composition of FAs in Abyssinian oil is a genetic trait, which is only slightly modified even under radically different agronomic and weather conditions [18,24,33,34] (this study, Table 6).

Hulled seeds of *C. abyssinica* cultivars grown in European Russia (Middle Volga Region) and Central Europe (Poland) accumulate 189–218 g kg⁻¹ DM total protein [36,37]. In the Mediterranean Region, the total protein content of hulled *C. abyssinica* seeds was higher by 50–70 g kg⁻¹ DM [33].

In the current study, the total protein content of *C. abyssinica* seeds ranged from 208 to 238 g kg⁻¹ DM and was typical for colder regions with a humid continental climate.

Regardless of genetic factors that affect nutrient synthesis in the seeds of *Brassica* crops, nutrient levels can be modified by climatic and soil conditions, and agronomic management [81]. In the group of agronomic factors, N [68,72,102,103,105,109,110] and S fertilization [68,81,111,112] play a key role in the biosynthesis of major nutrients and bioactive components in the seeds of oilseed crops of the family *Brassicaceae*.

Nitrogen influences the synthesis of reserve compounds that determine the protein and crude fat content of oilseed crops [54,113]. In most *Brassica* crops, N fertilization decreases the crude fat content and increases the total protein content of seeds. This trend was reported in *B. napus* [72] and other *Brassica* crops, including *C. sativa* [68,102,103,110], *B. juncea* [109], and *S. alba* [105]. Similar observations were made in this study, where N fertilization affected the qualitative and quantitative composition of fatty acids in *C. abyssinica* seeds. High rates of N fertilizer increased the content of linoleic acid and decreased the content of linolenic acid in Abyssinian oil. In a study by Chaves et al. [93], the protein and crude fat content of crambe seeds was not modified by increasing N rates.

Sulfur exerts varied effects on the crude fat and total protein content of *Brassica* seeds. In *B. napus* [114,115], *C. sativa* [68,102,103,116], and other oilseed crops of the family *Brassicaceae* (*B. napus*, *B. juncea*, *S. alba*), the relationship between S fertilization and the crude fat and total protein content of seeds appears to be less obvious [81]. In the current study, S fertilization exerted a minor impact on the total protein and crude fiber content of *C. abyssinica* seeds. The crude fat content of crambe seeds increased with a rise in S rate, and the strength of this association was determined by weather conditions. In the year with above-average precipitation, oil concentration in crambe seeds was highest after the application 15 kg S ha⁻¹. In the year with below-average precipitation, the crude fat content of seeds increased in response to the S rate of 30 kg ha⁻¹. Sulfur fertilization caused a significant decrease in the content of linoleic acid in Abyssinian oil, but did not affect the proportions of the remaining fatty acids or the total content of SFAs, MUFAs, and PUFAs.

5. Conclusions

Nitrogen fertilization increased plant height, shoot diameter at the base, the number of productive branches, the number of plants m⁻², and seeds plant⁻¹. Sulfur fertilization improved TSW. The growth-promoting effects of N and S fertilization on *C. abyssinica* were more pronounced in the year with above-average precipitation, from inflorescence emergence to fruit development. In NE Poland, the average seed yields of *C. abyssinica* ranged from 0.96 Mg ha⁻¹ in the dry year, to 1.64 Mg ha⁻¹ in the year with average precipitation, and 1.82 Mg ha⁻¹ in the year with above-average precipitation. The response of crambe plants to N fertilization was determined by precipitation. The N rate of 120 kg ha⁻¹ delivered satisfactory results in years with average and above-average precipitation, whereas N fertilization was not effective in the dry year of the experiment. Nitrogen rates of ≥60 kg ha⁻¹ decreased the HI in years with average and above-average precipitation. Nitrogen fertilization decreased the crude fat content and increased the total protein and crude fiber content of *C. abyssinica* seeds. Crambe seed yields continued to increase up to the S rate of 15 kg ha⁻¹, regardless of agroecological conditions in the experimental years. Sulfur fertilization was particularly effective when N was applied at >30 kg ha⁻¹ (22–39% increase in NFUE). Sulfur increased the crude fat content, but did not affect the concentrations of the remaining nutrients in crambe seeds. Abyssinian oil was most abundant in erucic acid (57–65%), and it also contained considerable amounts of oleic acid (15–19%) and linoleic acid (9–11%). Nitrogen fertilization increased the content of linoleic acid and decreased the content of linolenic acid, whereas S fertilization significantly decreased the content of linoleic acid in Abyssinian oil.

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supervision, M.S. and K.J.; project administration, K.J.; funding acquisition, K.J. All authors have read and agreed to the published version of the manuscript.

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