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Effects of Environmental Factors on Edible Oil Quality of Organically Grown *Camelina sativa*

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ABSTRACT: The aim of the present study was to evaluate the potential for the production of edible oil from organically grown camelina (*Camelina sativa* L. Crantz), focusing on the influence of environmental factors on nutritional quality parameters. Field experiments with precrop barley were conducted in Norway in the growing seasons 2007, 2008, and 2009. Trials were fully randomized with two levels of nitrogen (N) fertilization, 0 and 120 kg total N ha^{-1}, and two levels of sulfur (S) fertilization, 0 and 20 kg total S ha^{-1}. Weather conditions, that is, temperature and precipitation, were recorded. Additional experiments were performed in the years 2008 and 2009 to evaluate the effects of replacing precrop barley with precrop pea. Seed oil content was measured by near-infrared transmittance, and crude oil compositions of fatty acids, phytosterols, tocopherols, and phospholipids were analyzed by chromatography and mass spectrometry. Results showed significant seasonal variations in seed oil content and oil composition of fatty acids, tocopherols, phytosterols, and phospholipids that to a great extent could be explained by the variations in weather conditions. Furthermore, significant effects of N fertilization were observed. Seed oil content decreased at the highest level of N fertilization, whereas the oil concentrations of α-linolenic acid (18:3n-3), erucic acid (22:1n-9), tocopherols, and campesterol increased. Pea compared to barley as precrop also increased the 18:3n-3 content of oil. S fertilization had little impact on oil composition, but an increase in tocopherols and a decrease in brassicasterol were observed. In conclusion, organically grown camelina seems to be well suited for the production of edible oil. Variations in nutritional quality parameters were generally small, but significantly influenced by season and fertilization.

KEYWORDS: *camelina, organic, fertilization, n-3 PUFA, phytosterols, tocopherols*

INTRODUCTION

Camelina (*Camelina sativa* L. Crantz) is an underexploited, but promising, oilseed crop that may be well-suited for organic cropping in northern areas.[3] The seed quality makes it relevant for both edible oil and animal feed,[12,40,49] but so far the market is limited as well as the agronomic knowledge. Camelina seeds contain up to 45% oil, and the oil is particularly high in the omega-3 fatty acid α-linolenic acid (18:3), which constitutes 35−45% of the fatty acids.[38,40] α-Linolenic acid is converted to some extent to the long-chain omega-3 fatty acids eicosapentaenoic acid (EPA, 20:5) and docosahexanoic acid (DHA, 22:6) in the body,[5] and it has been shown that intake of camelina oil compared to rapeseed oil gives significantly higher serum concentrations of 18:3, EPA, and DHA, as well as a decrease in serum cholesterol in hypercholesterolemic subjects.[22] The health benefits of EPA and DHA are well documented, including protective effects on cardiovascular disease and autoimmune and mental disorders,[10,30,34] but there is also a growing body of scientific data supporting the idea that 18:3 may exert beneficial effects by other mechanisms rather than simply acting as a precursor for EPA and DHA.[8,11,17,35,51,52] Camelina oil also contains phytosterols known to have a cholesterol-lowering effect[23,32] and natural antioxidants such as tocopherols (vitamin E). Camelina oil is particularly rich in γ-tocopherol,[44] making it very resistant to oxidation.[12,46]

Camelina is a low-input and short-seasoned oilseed crop, with low nutrient requirement, no seed dormancy, and fewer problems with insect damage than rape and turnip rape. Fertilizers, as well as other environmental factors, may influence the nutritional quality of oilseeds, as demonstrated in conventionally grown crops,[4,15,41,50] but there is currently very little experience with oilseed crops in organic agriculture. Because sulfur deficiency may be a problem in organic fields,[18] and a balance between sulfur (S) and nitrogen (N) is necessary to obtain adequate yields and quality,[13,14,26] the effects of both N and S fertilization need to be established. It is not known to what extent limitations in the N supplement will influence the seed oil content or whether organic manure and mineral fertilizer will cause differences in oil quality. The overall aim of the present study was to evaluate the potential of growing camelina organically for secure production of high-quality edible oil by investigating the effects of environmental factors such as temperature, precipitation, and N and S fertilization on seed oil content and composition.

MATERIALS AND METHODS

Plant Materials and Chemicals. *C. sativa* L. Crantz cultivar Borowska was used in all field experiments. Tocopherols (α-, γ-, and δ-tocopherol) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Sterol standards, that is, cholesterol, cholestanol, brassicasterol, β-sitosterol, campesterol, campestanol, stigmasterol, and stigmastanol,

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were obtained from Sigma-Aldrich. Phospholipid (C15:0/C15:0 PE), used as internal standard, was obtained from Larodan Fine Chemicals AB (Malmoe, Sweden). All chemicals used in the study were of reagent grade.

Field Experiments. Field experiments were performed at Bioforsk Arable Crops, Apelsvoll, localized about 80 km north of Oslo, Norway. The experiments were performed on loamy soil with pH ranging from 5.6 to 6.1. The content of organic matter was between 3 and 12%. Trials were conducted for three growing seasons, 2007, 2008, and 2009, as fully randomized complete block trials with three replicates. Fertilization was added to 20 m^2 individual plots before seeding. Sowing time was early May, and sowing rate was held constant at approximately 4 kg ha^{-1} distributed by a conventional seed driller. Harvesting took place in late September when 8.4 m^2 in the center of each plot was harvested using a plot combine harvester. The previous crop was either barley or pea.

Trials were performed with two levels of nitrogen (N) fertilization, 0 and 120 kg total N ha^{-1} (chicken manure pellets), and experiments with precrop barley had in addition two levels of sulfur (S) fertilization ($CaSO_4 + 2H_2O$, powdered gypsum), 0 and 20 kg total S ha^{-1}. N and S levels were randomized within each replicate, and after harvest seed samples with similar fertilization treatment were pooled across the three replicates. A full factorial experimental design (pooled samples presented in Table 1) with precrop barley was used all three years to evaluate the effects of fertilizers (N and S) and season (2007, 2008, and 2009) on nutritional quality parameters in crude oil fractions. An additional experimental design (pooled samples presented in Table 2) was performed in 2008 and 2009 to evaluate the effect of replacing precrop barley with precrop pea.

Table 1. Design of Experiment 1 (Pooled Samples of Three Replicates): Precrop Barley

sample	sulfur (kg/ha)	nitrogen (kg/ha)	season (year)
1	0	0	2007
2	20	0	2007
3	0	120	2007
4	20	120	2007
5	0	0	2008
6	20	0	2008
7	0	120	2008
8	20	120	2008
9	0	0	2009
10	20	0	2009
11	0	120	2009
12	20	120	2009

Weather Conditions. Temperature at 2 m height (°C), soil temperature at 10 cm depth (°C), and precipitation (mm) were registered daily during the growing seasons 2007, 2008, and 2009.

Table 2. Design of Experiment 2 (Pooled Samples of Three Replicates): Precrop Barley or Pea, S Application = 0

sample	nitrogen (kg/ha)	season (year)	precrop
1	0	2008	pea
2	120	2008	pea
3	0	2009	pea
4	120	2009	pea
5	0	2008	barley
6	120	2008	barley
7	0	2009	barley
8	120	2009	barley

Sample Preparations. After harvest, the seeds were dried by natural air flow to 11% water content or less and cleaned. Seed samples were taken as pooled samples of three replicates in the field trials. Every sample was about 0.5 kg. The seed samples were kept in paper bags and stored in a cold-storage chamber at 5 °C at approximately 60% relative humidity. Crude oil fractions were obtained by using a pilot press for small samples (BT Bio Press Type 50, BT biopresser aps, Dybvad, Denmark). Oil fractions were stored at −40 °C prior to analysis. Pressing and analyzing crude oil in seeds from the different growing seasons, 2007, 2008, and 2009, took place at the same time at the end of the study (2009).

Seed Oil Content. The oil content (% oil in dry matter) was analyzed by near-infrared transmittance using an Infratec Grain Analyzer (FOSS Companies, Denmark), calibrated for oil crops (rapeseed (*Brassica napus* ssp. *oleifera*)).

Fatty Acid Composition. Fatty acids in the oil fractions were measured as fatty acid methyl esters using gas chromatography (GC) with flame ionization detection (FID). Briefly, lipids were derivatized and analyzed as methyl esters using capillary GC on a HP 6890 equipped with a BPX-70 column, 60 m × 0.25 mm i.d., 0.25 μm film (SGE Analytical Science Pty Ltd., Ringwood, Australia). The temperature program started at 70 °C for 1 min, increased by 30 °C/min to 170 °C, by 1.5 °C/min to 200 °C, and by 3 °C/min to 220 °C with a final hold time of 5 min. Peaks were integrated with HP GC ChemStation software (rev. A.05.02) (Agilent Technologies, Little Falls, DE, USA) and identified by use of external standards. Coefficients of variation were <5%. The concentrations of individual fatty acids were expressed in percent of total fatty acids. All results are based on duplicate analyses.

Tocopherols. The oil sample (250 μL) was pipetted directly into a HPLC vial and 250 μL of *n*-heptane added with internal standard and BHT and shaken. The vial was purged with nitrogen and sealed. A HPLC method based on that of Panfili et al.[37] that was further developed and in-house validated was used for the quantification of tocopherols. An Agilent 1050 series HPLC (Agilent Technologies, Santa Clara, CA, USA) was used for chromatographic separation of the tocopherols, interfaced with a Shimadzu RF-551 fluorescence detector (Shimadzu UK Limited, Buckinghamshire, UK) set to an excitation wavelength of 292 nm and an emission wavelength of 330 nm. Twenty microliters of sample was injected onto a Kromasil (silica) 250 × 4.6 mm column packed with 5 μm silica packing material (Thermo Electron Corp., Waltham, MA, USA). Mobile phase was run isocratically with 97.3% *n*-heptane, 1.8% ethyl acetate, and 0.9% acetic acid at a flow rate of 1.6 mL/min. Tocopherol isomer standards (Sigma-Aldrich, St. Louis, MO, USA) were used for identification and quantification based on retention time and expected isomer pattern. Concentrations (μg/g oil) of individual tocopherols were obtained from duplicate analyses. Total tocopherol content was calculated as the sum of α-, γ-, and δ-tocopherols.

Phytosterols. A modified method based on that of Toivo et al.[47] was used for analyzing the sterols. Approximately 0.03 g of oil was weighed accurately in a 50 mL glass centrifuge tube, and internal standard (5β-cholestan-3α-ol) was added. For saponification, 0.5 mL of saturated KOH and 7.5 mL of ethanol were added to the oil, mixed, and kept at 85 °C for 30 min. Twenty milliliters of cyclohexane and 15 mL of water were added to the cooled saponified sample and mixed, followed by centrifugation at 1000 rpm for 10 min. Four milliliters of organic phase was evaporated and then silylated with 100 μL of pyridine and 200 μL of BSTFA for 1 h at 40 °C. One microliter of sample was injected splitless into an Agilent 7890A gas chromatograph interfaced with a 5975C mass selective detector (Agilent Technologies, Little Falls, DE, USA). The phytosterol derivatives were separated on a HP-5MS fused silica capillary column (30 m × 0.25 mm × 0.25 μm) (Agilent Technologies, Little Falls, DE, USA) using helium as carrier gas at an average velocity of 26 cm/s (0.5 mL/min). The initial temperature was 100 °C for 1 min, then increased by 30 °C/min to 170 °C, then by 1.5 °C/min to 200 °C, and then by 3.0 °C/min to 220 °C and kept for 5 min. Mass spectrometer (MS) ion source temperature was 200 °C, with electron ionization energy of 70 eV. MS acquisition was recorded in both the TIC and SIM modes.

Identification of compounds was done by using EI spectra of standard compounds (Sigma Aldrich), and 5β-cholestan-3α-ol was used as internal standard for quantification. Concentrations (μg/g oil) of individual phytosterols were based on duplicate analyses.

Phospholipids. Oil fractions were dissolved in chloroform (50 μL oil to 3.5 mL chloroform) and separated into lipid classes, that is, neutral lipids (glycerides), free fatty acids, and polar lipids (phospholipids), by automated solid phase extraction (SPE) (Gerstel MPS Autosamler, Gerstel GmbH, Switzerland) based on a modified and in-house validated method.[42] Phospholipids were eluted with 0.05 M sodium acetate in methanol/chloroform (6:1). The solvent was removed by evaporation under N_2, and the contents of fatty acids in the phospholipid fraction were measured as fatty acid methyl esters using gas chromatography (GC) with flame ionization detection (FID) as described above (Fatty Acid Composition). An internal standard (C15:0/C15:0 PE) was used for quantification of the total amount of fatty acids in phospholipids (mg/g oil).

Statistical Methods. Statistical analyses were performed using Unscambler v 9.8 (Camo Inc., Oslo, Norway). Significant main effects and interaction effects (2-var) of fertilization (N and S), growing season (2007, 2008, and 2009), and precrop (barley or pea) (Tables 1 and 2) were analyzed by classical DOE (design of experiments) analysis using the multiple linear regression (MLR) and Scheffé formulas.[43] Nominal level for significance was 5%. Principal component analysis (PCA) and partial least-squares (PLS) regression were performed to find relationships between variables and to find variations in the weather conditions that could best predict variation in oil quality. To make realistic comparisons, variables were weighted before regression analysis. Regressions were validated by full cross-validation.[29]

RESULTS

Weather Conditions. Precipitation and temperatures at Apelsvoll in the growing seasons 2007, 2008, and 2009 are shown in Figure 1. Season 2007 had higher temperatures and rainfall in June, but a very dry August compared to 2008 and 2009. Season 2009 had a high rainfall in July compared to the two other years. The main difference in temperature was in June and July, with the highest temperatures in 2008 in July and the highest temperatures in 2007 in June. The mean temperature in September was highest in 2009.

Seed Oil Content and Composition: Field Experiments with Precrop Barley. In general, observed seasonal variations were slightly larger than variations caused by application of fertilizers (Tables 3, 5, and 6). The average oil content in seeds of camelina from the growing seasons 2007, 2008, and 2009 varied from 40.4 to 41.8% (p = 0.0008), linoleic acid (18:2) from 15.5 to 16.4% (p < 0.0000), α-linolenic acid (18:3) from 36.7 to 38.1% (p = 0.0083), eicosenoic acid (20:1) from 14.8 to 15.0 (not significant), and erucic acid (22:1) from 2.7 to 3.0% (p < 0.0000). Seeds harvested in 2009 had the lowest content of 18:3 and 22:1 and the highest content of 18:2. The total contents of fatty acids in phospholipids varied from 5.09 to 15.00 mg/g, showing distinct seasonal variations (p = 0.0038) with higher contents in 2007 compared to 2008 and 2009 (Table 4). The fatty acid composition in phospholipids varied slightly from the total fatty acid composition with more palmitic acid (16:0) and stearic acid (18:0) and less unsaturated fatty acids (Tables 3 and 4). However, seasonal variations in the fatty acid composition of phospholipids reflected those observed in crude oil fractions. Average concentrations of tocopherols in crude oil from seeds harvested in 2007, 2008, and 2009 varied from 720.5 to 814.2 μg/g (p < 0.0000), and phytosterols varied from 4.34 to 4.67 mg/g (p = 0.0028) (Table 5). The highest levels of tocopherols and phytosterols were observed in 2008.

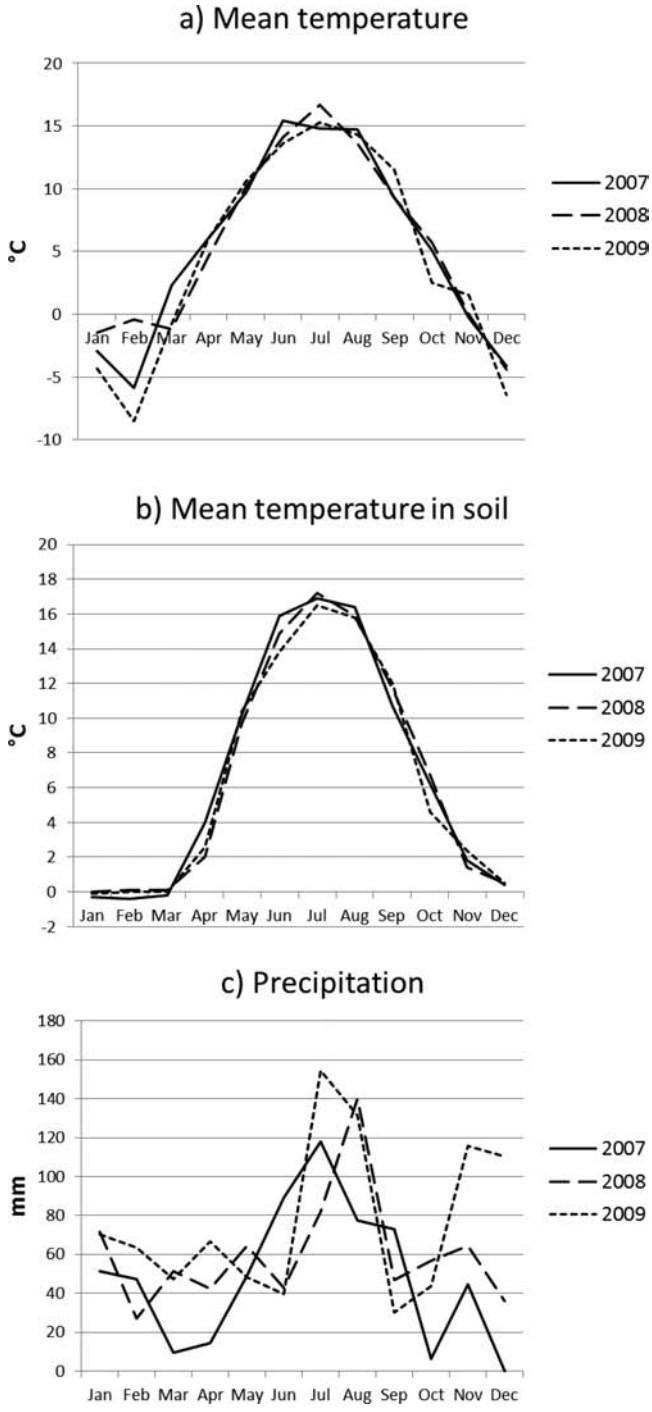

Figure 1. (a) Mean temperature (°C) at 2 m height, (b) mean soil temperature (°C) at 10 cm depth, and (c) precipitation (mm) during the seasons 2007, 2008, and 2009.

DOE analysis further revealed that increased N fertilization caused a decrease in seed oil content (p = 0.0142), but increased oil concentrations of 16:0 (p = 0.0226), 18:3 (p = 0.0008), and 22:1 (p < 0.0000) and decreased levels of oleic acid (18:1) (p = 0.0198) and linoleic acid (18:2) (p = 0.0007). N fertilization also gave significant increases in the oil concentrations of γ-tocopherol (p = 0.0003), total tocopherols (p = 0.0001), and campesterol (p = 0.0130). No effects were observed on phospholipids. S fertilization had little impact on seed oil content and oil composition, but an increase in the

Table 3. Camelina Seed Oil Content and Fatty Acid Composition at Different N Applications in 2007, 2008, and 2009 with Precrop Barley

	2007		2008		2009	
N application	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha
fatty acid (% of fatty acids)						
C16:0	5.1	5.2	5.3	5.4	5.3	5.4
C18:0	2.4	2.4	2.5	2.4	2.5	2.5
C18:1n-9	13.2	12.5	12.8	12.5	13.7	12.9
C18:2n-6	15.6	15.3	15.8	15.6	16.5	16.3
C18:3n-3	37.6	38.6	37.3	37.6	36.4	36.9
C20:1n-9	15.0	14.9	14.9	14.7	14.8	15.1
C22:1n-9	2.8	2.9	2.9	3.0	2.6	2.7
seed oil content (% of dry matter)	41.8	40.8	40.6	40.1	41.9	41.7

Table 4. Fatty Acids in Phospholipids in Camelina Seed Oil from 2007, 2008, and 2009 with Precrop Barley

	2007	2008	2009
fatty acid (% of fatty acids in phospholipids)[a]			
C16:0	10.1 ± 1.4	11.8 ± 0.6	11.8 ± 0.2
C18:0	5.2 ± 2.3	4.4 ± 0.9	5.8 ± 0.3
C18:1n-9	15.9 ± 0.4	15.4 ± 0.7	17.4 ± 2.3
C18:2n-6	19.5 ± 0.7	21.7 ± 0.9	21.6 ± 0.8
C18:3n-3	35.5 ± 1.7	32.7 ± 0.5	28.5 ± 2.1
C20:1n-9	11.5 ± 0.5	11.3 ± 0.4	12.5 ± 0.9
C22:1n-9	2.2 ± 0.1	2.7 ± 0.6	2.5 ± 0.3
total fatty acids in phospholipids (mg/g seed oil)[a]	15.0 ± 3.5	5.1 ± 0.9	6.0 ± 2.9

[a]Values given as mean ± standard deviation.

content of total tocopherols (p = 0.0363) and γ-tocopherol (p = 0.0584) was found, as was a decrease in the level of brassicasterol (p = 0.0135). The effects of S application were slightly higher when N application was low (interaction effect, p < 0.032). Otherwise, there were no significant interaction effects between growing season and N and S on any of the parameters investigated.

PCA clearly demonstrated that for all three years, 2007, 2008, and 2009, the levels of 16:0, 18:3, 22:1, tocopherols, and phytosterols were inversely associated with seed oil content and levels of 18:1 and 18:2, reflecting the effects of fertilization. Only the PCA plot from year 2007 is shown (Figure 2). PLS regression was performed with weather conditions (temperature and precipitation) as X variables and oil quality parameters as Y variables (Figure 3). Including soil temperature as a variable in the models did not increase explained variance and was therefore left out. Results demonstrated that the observed variations in seed oil content and oil composition could partly be explained by changes in weather conditions, revealing an overall explained variance equal to 53%. Explained variances were 67% for phospholipids, 62% for phytosterols, 70% for tocopherols, and 60% for 18:3. The increased levels of phospholipids were associated with high rainfall and high temperatures in June and low rainfall and higher temperatures in August. The levels of phytosterols and tocopherols were highly correlated (r = 0.826) and inversely associated with seed oil content and levels of phospholipids. High levels of phytosterols and tocopherols were associated with low rainfall and high temperatures in July.

Seed Oil Composition: Field Experiments with Precrop Pea. Designed experiments performed in 2008 and 2009 (Table 2) indicated that pea compared to barley as precrop had similar effects on the fatty acid composition as N fertilization, with a significant increase in the content of 18:3 (p = 0.0352) and a decrease in the content of 18:2 (p = 0.0258). Also, small, but significant, increases in the contents of δ-5-avenasterol (p = 0.0024) and cholesterol (p = 0.0433) were observed, whereas there were no significant effects of precrop on tocopherol content.

DISCUSSION

The present study shows that nutrient levels in crude oil from organically grown camelina are similar to what is found in conventionally grown camelina.[1,9,44,53] The most abundant fatty acid is α-linolenic acid 18:3 (33−41%), and the most abundant tocopherol is γ-tocopherol (720−940 μg/g oil).[1,20,53] Among the phytosterols (3604−5110 μg/g oil), sitosterol and campesterol are the most dominating, but significant amounts of cholesterol, brassicasterol, and δ-5-avenasterol are also present.[44,45] The present results further indicate that environmental factors such as temperature, precipitation, and N and S fertilization influence both seed oil content and nutrient levels. This is in line with previous studies of conventionally grown camelina, suggesting that the oil quality characteristics are strongly influenced by environmental factors.[15] However, relatively small seasonal variations were observed in the present

Table 5. Contents of Tocopherols in Camelina Seed Oil at Different N Applications in 2007, 2008, and 2009 with Precrop Barley[a]

	2007		2008		2009	
N application	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha
α-tocopherol	26.4	25.4	26.4	25.8	25.6	23.8
γ-tocopherol	661.2	705.9	763.5	787.2	701.1	739.3
δ-tocopherol	11.5	10.5	11.5	13.9	9.1	10.3
total tocopherols	699.1	741.9	801.3	827.0	735.8	773.4

[a]Values are given as μg/g seed oil.

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Table 6. Contents of Phytosterols in Camelina Seed Oil at Different N Applications in 2007, 2008, and 2009 with Precrop Barley[a]

	2007		2008		2009	
N application	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha	0 kg/ha	120 kg/ha
cholesterol	325	319	340	347	317	324
brassicasterol	359	359	410	425	373	380
campesterol	1052	1105	1148	1186	1110	1128
sitosterol	2198	2249	2361	2374	2233	2256
δ-5-avenasterol	364	353	356	389	344	359
total phytosterols	4298	4385	4615	4721	4377	4447

[a]Values are given as μg/g seed oil.

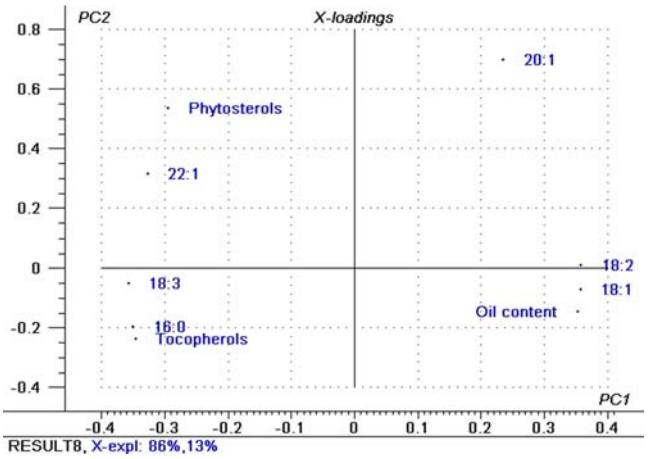

Figure 2. Principal component analysis of quality parameters in camelina crude oil from growing season 2007.

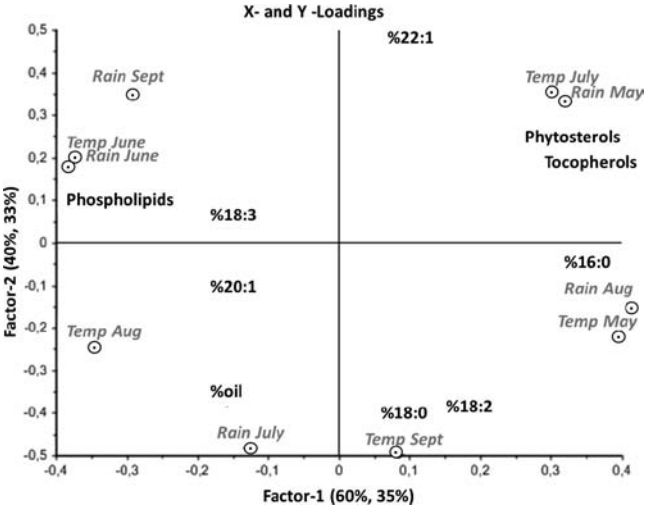

Figure 3. Partial least-squares regression analysis of data from growing seasons 2007, 2008, and 2009. *X*= weather conditions (temperature and rainfall from May to September), and *Y* = seed oil quality parameters.

study, probably because the study was conducted at the same geographic location with minor fluctuations in climatic conditions. Moreover, seeds from all three growing seasons were pressed and analyzed simultaneously at the end of the study, thereby avoiding time-dependent variations in method performance. Alternatively, seeds could have been analyzed during the respective years to avoid possible storage effects. However, the present results show higher contents of tocopherols and phytosterols in 2008 than in 2007 and 2009, suggesting that seed storage did not severely influence oil quality.

The lowest oil content and highest oil concentrations of phytosterols and tocopherols were observed in 2008 when temperature was highest and rainfall lowest in July, during flowering. The highest levels of α-linoleic acid (18:3) and phospholipids were observed in 2007, which had higher temperatures and excessive rainfall in June, that is, before and during flowering, and lower rainfall and higher temperatures in August, when flowering was finished and seed filling and maturation took place. The results indicate that the contents of phytosterols, tocopherols, and phospholipids are associated with temperature and precipitation during seed development. It is well documented that drought conditions may provoke substantial alterations in the lipid composition of plasma membranes[36,39] where sterols, tocopherols, and phospholipids constitute essential parts. The present results (Figure 3) also support the suggestion that reduction in seed oil content is inversely associated with average daily temperature during seed development.[6,7] It is, however, difficult to point out which particular climatic change had the highest impact on the measured parameters. More growing seasons need to be included to introduce sufficient variations to reach clear conclusions about climatic effects on seed oil content and oil composition. In the present study climatic variations (temperature and precipitation) explained 53% of the variations in oil quality parameters, whereas soil temperature did not increase explained variance any further. However, it is not known to what extent environmental parameters not registered, such as soil composition and salinity, contributed to the observations.

Variations caused by application of fertilizers were in general smaller than variations observed between growing seasons. Results indicate that S fertilization has little impact on seed oil content and oil composition in camelina. Significant effects were, however, observed in the oil contents of tocopherols and brassicasterol, and the effects were slightly higher when the level of N fertilization was low. The findings of Losak et al.[26,27] that S application tends to increase oil concentration in camelina could not be confirmed in the present study. Whether this was due to lower S rates (0−20 kg S ha^{-1}) than those used by Losak et al. (75−135 kg S ha^{-1}) or differences in natural S level in the soil is not known. Enhanced oil accumulation in developing seeds with S fertilization has also been observed in rapeseed.[2]

The existing literature indicates that N application significantly affects seed oil content and seed quality in oil crops.[26,33,48,50] Studies of camelina have shown that increasing N rates up to 127 kg ha^{-1} reduces seed oil content, but increases seed yield and subsequently the total oil yield.[27] Data

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from the present study showed an increase in seed yield from 1504 to 1996 kg ha^{-1} with increasing N rates (0−120 kg ha^{-1})[19] and a decrease in seed oil content was observed as well. The results further demonstrated that the decrease in oil content was accompanied by improved nutritional oil quality with higher concentrations of 18:3, tocopherols, and phytosterols. Similar effects were observed when precrop barley was replaced by pea, probably due to pea being a highly efficient N fixing crop providing the soil with large amounts of N to the subsequent crop.[21]

N fertilization also increased the oil content of erucic acid (22:1n-9), which may be a matter of concern. High intakes of erucic acid have been associated with cardiac lipidosis in animal studies.[16,24,25,31] However, the present results show that the content of erucic acid was ≤3% which is well below the maximum allowed level of 5% in edible oils in the European Union. Cruciferae seem to be easily manipulated through plant breeding or biotechnology,[28,40] so it is likely that this trait could readily be removed, as it has been with rapeseed (*Brassica napus* L.). Camelina also seems to be unique among oilseed crops in having a high content of eicosenoic acid (20:1n-9), but the potential value or disadvantage of this is currently unclear.

Camelina oil has a great potential for exploitation in human nutrition due to its high contents of 18:3, tocopherols, and phytosterols. The oil is also considered to be more stable toward oxidation than other highly unsaturated oils, probably due to the high levels of γ-tocopherol, but also phenolic compounds, such as chlorogenic acid, may contribute to the protection against oxidation.[1,20,53] Whether there are differences between organically and conventionally grown camelina with respect to contents of phenolic compounds needs to be investigated. Natural antioxidants and phospholipids are best preserved in cold-pressed oil, but crude camelina oil has a distinct smell and taste that may be difficult to find acceptance among consumers. Studies should therefore be performed to remove undesirable flavor and at the same time ensure both a long shelf life and high nutritional quality.

In conclusion, organically grown camelina seems to be well-suited for production of edible oil. The present results indicate that season, precrop, and levels of S and N fertilizers significantly influence seed oil content and composition. In particular, the oil content of phospholipids showed distinct variation between growing seasons. Higher amounts of phospholipids and 18:3 and lower contents of saturated fatty acids were associated with lower rainfall and higher temperatures in August during seed filling and maturation, whereas higher contents of tocopherols and phytosterols were associated with lower rainfall and higher temperatures in July when flowering took place. N fertilization caused a decrease in oil content and increased oil concentrations of 18:3, tocopherols, and campesterol.

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Author Contributions

B.K., statistical analysis and interpretation of data, writing the manuscript; A.R.L., design of experiments, analysis and interpretation of data, writing the manuscript; J.-E.H., analysis and interpretation of data, revising the manuscript; G.V., analysis and interpretation of data, revising the manuscript; G.I.A.B., analysis and interpretation of data, revising the manuscript; B.I.F.H., design of experiments, analysis and interpretation of data, writing the manuscript.

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Notes

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ABBREVIATIONS USED

ANOVA, analysis of variance; DHA, docosahexanoic acid; DOE, design of experiments; EPA, eicosapentaenoic acid; HPLC, high-performance liquid chromatography; GC, gas chromatography; MLR, multiple linear regression; MS, mass spectrometer; N, nitrogen; PCA, principal component analysis; PLS, partial least-squares; S, sulfur

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