Chapter

Agronomic Response of Camelina to Nitrogen and Seeding Rate on the Northern Great Plains

Thandiwe Nleya, Dwarika Bhattarai and Phillip Alberti

Abstract

Camelina (*Camelina sativa* L. Crantz,) a new oilseed crop in the Brassicaceae family has favorable agronomic traits and multiple food and industrial uses. Appropriate production practices for optimal camelina yield in temperate climates of North America are lacking. This study investigated the response of camelina seed yield and quality, and agronomic traits to applied N (5 levels, 0, 28, 56, 84, 140 kg ha^{-1}) and four seeding rates (4.5, 9, 13, 17.5 kg ha^{-1}). Separate experiments were conducted at four environments (site-years) for N and three environments for seeding rate in South Dakota. In three of the four environments, the highest N rate increased seed yield by 30 to 60% compared to the control. The increase in seed yield with increasing N rate was linear in a high yielding environment and quadratic in a low yielding environment. Increasing seeding rate increased plant stands but had inconsistent impacts on seed yield depending on location and year. Seed oil concentration ranged from 149 to 350 g kg^{-1}, was inversely related to N rate but was not influenced by seeding rate.

Keywords: *Camelina sativa* L., camelina, N fertilizer, seeding rate

1. Introduction

Camelina (*Camelina sativa* L. Crantz,) commonly known as camelina or false flax, is an annual herbaceous oilseed crop commonly grown in the temperate region of Europe and North America [1]. Although the actual origin of this crop is uncertain, most studies report that the crop likely originated in southeastern Europe and southwestern Asia [2, 3]. Camelina was introduced as a weed in North America; however, at present, it is widely grown as an oilseed crop that can perform well in diverse climate, requires low nutrient and is highly resistant to diseases and pests [2, 4]. Camelina seed oil has diverse uses including edible products, biodiesel feedstock [4, 5], bio-jet fuel [4, 6] and other chemical derivatives [7, 8]. Seed oil content is reported to range from 26.7% to 46.0% [9, 10]. Camelina oil mainly consists of poly- and mono-saturated fatty acids. The most important ones are linolenic (C 18:3, 25–42.52%), linoleic (C 18:2, 12.34–21.3%), oleic (c 18:1, 11.89–20.51%) and eicosenic acid (C 20:1, 12,54–18.30%) [10]. Other notable fatty acids include palmitic (C 16:0), stearic (C 18:0), eicosanoic (C 20:0), and erucic (C 22:1) [8]. Because the oil is high in omega-3 (linolenic) and omega-6 (linoleic) acids and low in saturated fatty acids, the crop is considered a high quality edible oil. The oil also contains vitamin E which acts as an antioxidant and also increases the stability and the shelf life of camelina oil compared to other omega-3 oils [11]. Camelina oil has a high smoke point (246°C) and therefore can withstand high-heating cooking methods like frying. However, overheating the oil can reduce beneficial compounds such as antioxidants and can impact the overall taste of the oil so it is not recommended that camelina oil be heated for prolonged periods of time. The erucic acid (C 22:1) content of camelina oil is variable depending on the genotypes and can range 2.11 to 4.30% [10] higher than the maximum allowed in food grade rapeseed oil (2%) [11]. High content of erucic acid in edible oils is of concern as excessive consumption of erucic acid has often been linked to heart diseases. However, there is significant genetic variation for erucic acid and camelina breeding lines with lower erusic acid have been identified [11]. Camelina meal can be used as animal feed including cattle, swine and poultry [12–14] and has been reported as a potential aquaculture feed [15]. The increasing demand of high quality biofuel derived from polyunsaturated fatty acids, [16], has prompted interest for the development of sound agronomic practices for camelina production as an industrial oilseed in Northern Great Plains (NGP) of the US. Thus, there is a need to identify the optimal management practices for camelina including seeding rate, and nitrogen (N) fertilization for achieving yield and seed quality goals in both humid temperate and semi-arid production zones of the NGP.

Nitrogen is an important component required for physiological functions of all plants; it has a crucial role in photosynthesis and is a component of protein and enzymes. Many studies have suggested that camelina has a low nitrogen requirement compared to other oilseed crops like canola and sunflower. Research conducted in Kansas, US reported that N fertilizer application affected plant height, plant stand, protein content of camelina seeds, and biomass and seed yield [9]. The optimum N rate was 50 kg ha^{-1} producing about 760 kg ha^{-1} seed yield suggesting camelina has a low N requirement. This was supported by other research results conducted in US [17–19]. More recently, in a study conducted in Minnesota, US, Johnson et al. [17] reported that a rate of 34 kg ha^{-1} N was sufficient to achieve economically viable camelina seed and oil yields. Mohammed et al. [18] reported that application of 60 kg ha^{-1} N produced maximum seed yield and oil yield while Wysocki et al. [19] reported optimum N rates ranging from 0 to 90 kg ha^{-1} depending on annual precipitation and available N. On the other hand, Solis et al. [20] reported that under conditions of high productivity, camelina maximum seed yield is achieved at N rate of 185 to 300 kg ha^{-1} N. These findings were supported by Malhi et al. [21] who reported that camelina responded to high N rates (170 kg ha^{-1}) similar to *Brassica juncea* and Jiang and Caldwell [22] who concluded that camelina responded positively to increased N rates up to 200 kg ha^{-1} but that seed yield response to applied N depended on genotype. Previous research seem to agree however, that seed oil content decreases as N application rate increases [18, 20, 22]. The above research shows that the response of camelina to increasing N rate varies considerable depending on environmental conditions.

Stand establishment varies depending on tillage practices, environmental conditions and variety and therefore higher seeding rates are often recommended to avoid stand losses due to poor seedbed conditions. In camelina as with most agronomic crops, uniform crop emergence and plant development are crucial to achieving optimum yields and using the appropriate seeding rate is very important to achieve this goal. Previous studies on impact of seeding rate on camelina yield often suggest that yield is not reduced by low plant populations due to growth plasticity of camelina plants [23–25]. Optimum seeding rates for camelina range from 4 to 6 kg ha^{-1} [8]. In a study conducted in Canada optimum seeding rates ranged 400 to 600 seeds m^{-2} [25], which is similar with the recommendation suggested by Berti, et al., [8]. Gesch et al. [23] recommended a seeding rate of no less than 3 kg ha^{-1} for good stand establishment of spring camelina when seeded using a drill. Although these low seeding rates would be enough for optimum yield, higher seeding rates are often recommended to compensate for low stand establishment due to poor seedbed preparation, lack of soil moisture and poor competition of camelina with weeds. This means further evaluations under different environmental conditions are warranted.

The overall goal of this study is to develop management strategies for camelina production practices at two growing different agro-zones in South Dakota. The specific objectives were to determine the effects of N fertilization rate and seeding rate on growth, seed yield and seed oil content of camelina.

2. Material and methods

2.1 Study site

The study was conducted at two locations, near Brookings (44° 18' 40.8863" N, 96° 47' 54.1957" W) and near Pierre (44° 22' 5.9362" N, 100° 21' 3.4794" W) in South Dakota in 2015 and 2016 for N fertilization study and 2016 and 2017 for the seeding rate study. The Brookings study was conducted on a Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludolls) while the Pierre study was conducted on a Dorna silty loam soil (coarse-silty over clayey, superactive, mesic Fluventic Haplustolls). The previous crop at the Brookings location was winter wheat (*Triticum aestivum* L.) in all three years. At the Pierre location, the previous crops were teff [*Eragrotis tef (Zucc.)Trotter*] in 2015 and corn (*Zea mays* L.) in 2016 and 2017. Soil analysis details for each location in each year are shown on **Table 1**. Soils at each location were sampled in the spring of each year at planting time. Four soil cores were sampled diagonally across each field using a tee-handled push probe to a depth of 0–15 cm. At the Brookings location, the study was managed using conventional tillage while at Pierre the study was under no-tillage system.

2.2 Nitrogen fertilization study

The experimental design was a randomized complete block design with treatments replicated four times. Treatments included five different N fertilizer rates: 0, 28, 56, 84, and 140 kg N ha^{-1}, and one camelina variety (S-40). Nitrogen fertilizer in the form of urea (46% N), was broadcast manually on each plot soon after planting using an automatic hand-held spreader to ensure even application. In 2015, plots were planted on 3 April at Brookings and 16 April at Pierre. In 2016 the planting dates were 26 April at Brookings and 14 April at Pierre. Planting was accomplished

Location	Year	Texture class	pH	Soluble salts (mmho/cm)	Organic matter (%)	Nitrogen-NO3 (ppm)	Olsen-P (ppm)	K (ppm)
Brookings	2015	Medium	5.7	0.2	4.8	12.0	9.0	171.0
Brookings	2016	Medium	5.6	0.1	4.8	12.0	16.0	349.0
Brookings	2017	Medium	5.6	0.1	4.7	10.0	10.0	141.0
Pierre	2015	Medium	6.1	0.2	2.9	10.8	8.9	208.0
Pierre	2016	Medium	6.1	0.2	3.0	18.1	21.7	626.0

Table 1.
Site description and soil characteristics at the 0–15 cm depth for the two South Dakota locations where studies were conducted in 2015 and 2016.

using a seven-row Hege 500® (Wintersteiger- Austria) at Brookings; seeding at Pierre was done using a Light Duty Grain Drill® (Almaco- Iowa). Individual plot size was 1.6 x 9.1 m (14.6 m^2) at Brookings and 1.6 x 8.2 m (13.1 m^2) at Pierre. Each plot had seven rows, 22 cm apart. The seeding rate was 9 kg ha^{-1} at both locations.

Number of days to maturity were recorded when 50% of pods on the main stem of plants within a plot had turned yellow. Plant height was determined by measuring height of five random plants within each plot from soil line to the top of the plant and averaging the height. Yield was determined by harvesting whole plots using a Kincaid 8XP® crop research combine (Kincaid Equipment and Manufacturing- Haven, KS) with the assistance of the H2 High Capacity GrainGage® (Juniper Systems Inc.- Logan, UT). In 2015, camelina was harvested on 12 August at Brookings and 14 August at Pierre. In 2016, the study was harvested on 9 August at Brookings and 6 August at Pierre. Seed from each plot was dried to a constant weight, cleaned and sieved before weighing to determine seed yield.

2.3 Seeding rate study

The experimental design was a randomized complete block (RCBD) design with treatments replicated four times. Treatments included four different seeding rates (4.5, 9, 13, and 17.5 kg ha^{-1}) and two camelina cultivars ('SO-40 and SO-50) arranged in a factorial design to give a total of eight treatments. In 2016, the planting dates were April 26 at Brookings and April 15 at Pierre. In 2017, the planting dates were April 24 at Brookings. Planting was accomplished using a seven-row Hege 500® (Wintersteiger- Austria) at Brookings; seeding at Pierre was done using a Light Duty Grain Drill® (Almaco- Iowa). For the Brookings location, individual plot size was 1.62 x 9.14 meters (14.86 m^2) and 1.62 x 8.23 meters (13.37 m^2) at Pierre. Each plot had seven rows, 22 cm apart.

In 2016, 56 kg ha^{-1} N fertilizer in the form of urea (46% N) was broadcast manually using an automatic hand-held spreader to ensure even application ~4 weeks after planting. In 2017, 112 kg ha^{-1} N and 22 kg ha^{-1} S in the form of urea (46% N) and ammonium sulfate (21% N and 24% S) mixture was applied in a split application to ensure continuous supply of N. The first application occurred at planting and the second application occurred around the bolting stage. The fertilizer was broadcast manually using an automatic hand-held spreader to ensure even application.

Four weeks after seeding, plant stands were assessed by counting the number of plants in a 4 ft^2 and converted to plants m^{-2}. Days to flowering (50% of flowers open within each plot) and days to maturity (50% of plant with pods turned yellow within each plot) were also determined for each plot. At physiological maturity, average plant height was determined by measuring height of five random plants within each plot from soil line to the top of the plant. Lodging notes were taken and rated on a scale from 1 to 9 (1 = no lodging, 9 = completely lodged). Shattering notes were taken based on percent of pods shattered at the time of harvest within each plot. In 2016 only, random 10 plant samples were obtained from all plots and both locations, the number of seeds per 15 pods and number of pods per 10 plant determined. From these values, the average number of seeds pod^{-1} and pods $plant^{-1}$ were determined.

Once camelina had appropriately dried down, it was harvested using a Kincaid 8XP® crop research combine (Kincaid Equipment and Manufacturing- Haven, KS) with the assistance of the H2 High Capacity GrainGage® (Juniper Systems Inc.- Logan, UT). In 2016, the camelina was harvested on August 9 at Brookings and August 5 at Pierre. In 2017, the camelina was harvested on August 21 at Brookings.

2.4 Oil analysis

For both the N fertilizer and the seeding rate study, once the plots were harvested the seed was cleaned using a sieve and a blower to remove unwanted plant material; cleaned seed was collected and total seed yield (kg) was determined. Sub-samples of the harvested seed were collected and placed into individual manila envelopes and stored in a cold room (~10° C) for oil content determination. Two replications for all treatments were sent to SGS Mid-West Seed Services, Inc. (Brookings, SD, USA) for oil content analysis using a hexane solvent extraction. The results of this analysis were used to calibrate the "minispec mq" (Bruker- Billerica, Massachusetts) NMR instrument for further camelina oil analysis. The remainder of the samples from both years and locations were then analyzed using the "minispec mq."

2.5 Weed management

For both experiments, weeds were managed with pre-plant application at all locations of Prowl H_20 (Pendimethalin, BASF, Research Triangle, NC) herbicide. The herbicide was applied at a rate of 2.8 L ha^{-1} and incorporated 5 cm deep via two-pass incorporation. Herbicide application was at approximately two weeks before planting for both locations and all years. Once the crop had emerged, weeds were managed by manually removing weeds from within each plot, as necessary.

2.6 Statistical analysis

Data collected from each year were analyzed using PROC MIXED in SAS (Version 9.4, SAS Institute, Cary, NC) to determine the impact of N fertilizer and seeding rate on agronomic traits, seed and oil yield. The fixed effects in the model were N fertilizer rates in the first experiment and seeding rate and varieties in the second experiment while replication was considered random. The LINES option of LSMEANS statement was used to compare the differences among treatments at 95% confidence level. Different models (linear plateau, quadratic and quadratic plateau) were fit to seed yield, and seed oil concentration data to examine the response to N fertilizer rate. The choice of the best model was based on model significance (significantly different from zero based on t-test at P = 0.05), and coefficient of determination (R^2) [26, 27]. A Shapiro–Wilk test was used to test for normality.

3. Results and discussion

3.1 Climatic information

Temperature and rainfall data were collected at weather stations located within each farm throughout the crop growing period in both years (**Tables 2** and **3**). The climate data shows that the Pierre location was drier (especially during June and July) and hotter than the Brookings location. Overall, the 2015 growing season had rainfall and temperature conditions closer to the 30-year average at both locations. The trials were planted early to late April and the crop reached the flowering stage 52–56 days after planting meaning flowering and seed filling occurred in June and July. In 2016, both Brookings and Pierre had lower than average rainfall in June and July, coinciding with bolting, flowering, and seed filling periods, a critical time for seed development and quality. In particular, the Pierre location experienced higher temperatures and lower precipitation for a longer duration during this critical growth stage resulting in lower yields at this location.

	April	May	June	July	August	Total
	Rainfall (mm)					
Brookings 2015	5.1 (−49.0)	137.2 (+62.3)	43.2 (−65.8)	111.8 (+28.7)	71.1 (−6.9)	368.3 (−30.7)
Brookings 2016	48.3 (−5.8)	60.2 (−14.7)	66 (−43.0)	124.5 (+41.4)	142.2 (+64.2)	441.2 (+42.2)
Brookings 2017	40.7 (−13.5)	88.9 (+14.0)	5.1 (−103.9)	160.0 (76.9)	157.5 (+79.5)	542.1 (+53.0)
Pierre 2015	12.4 (−33.6)	157.0 (+77.0)	96.2 (+6.4)	58.2 (−7.4)	63.2 (+17.2)	387 (+59.6)
Pierre 2016	99.6 (+53.6)	30.5 (−49.5)	70.9 (−18.9)	28.5 (−37.1)	54.4 (+8.4)	283.9 (−43.5)

Table 2.
Monthly total rainfall throughout the crop growing period for camelina grown at Brookings and Pierre, SD in 2015, 2016 and 2017 (numbers in parentheses indicate deviations from 1981 to 2010 average).

3.2 N fertilizer effects

The N rate effects on plant height were significant at both locations in 2016 but were not significant in 2015 at both locations (**Tables 4** and **5**). At both locations in 2016, plant height increased with increasing N rate with the tallest plants recorded in the highest N rate of 140 kg ha^{-1}. These results agree with previous research on camelina where plant height increased with increasing N rate was inconsistent among environments [20]. In their study and in the current study, higher rates of N increased plant lodging. The influence of N rate on plant height and therefore lodging should be taken into consideration in environments with potential lodging problems such as areas with high wind speeds and high rainfall.

The number of days to maturity was recorded only in 2015 and was significantly influenced by nitrogen rate at both locations (**Table 4**). Days to maturity increased in response to N rate with a rate of 140 kg N ha^{-1} resulting in the longest time to maturity while plants in the control treatment took the shortest time to reach maturity (**Table 4**). These results confirm findings from previous studies suggesting that increased N fertilization rates can result in delayed crop maturity, due to prolonged periods of vegetative growth [28, 29]. Prolonged vegetative growth in the NGP would delay flowering and seed setting, the two most important growth stages determining yield potential, to later in the season (late-June–July) when high temperature and drought stress often occur. Under such environmental conditions, earlier planting dates and promoting earlier and shortened duration of flowering to avoid unfavorable conditions have been shown to increase yield in *Brassica* species [30, 31].

Seed yield was significantly influenced by nitrogen rate at Brookings in 2015 and at both locations in 2016 (**Tables 4** and **5**). At Brookings in 2015, N rates of 28 to 140 kg ha^{-1} yielded the same and significantly greater than the control. In 2016, on the other hand, the highest N rate of 140 kg ha^{-1} yielded greater than all other N rates and the control at the Brookings location. At a drier environment in Pierre, N rate did not impact seed yield in 2015 but in 2016, seed yield increased in response to N rate, with greatest seed yields occurring at the N rate of 140 kg N ha^{-1} rate (817 kg ha^{-1}) with this value statistically different from the yield obtained at all other N rates. The control treatment yielded significantly lower (416 kg ha^{-1}) than all other N rates. The effects of N fertilizer on seed yield of camelina have been reported by other researchers [20–22]. Jiang and Caldwell [22] reported that seed yield responded positively

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	April		May		June		July		August	
Location	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Avg.**
	Temperature ^{0}C									
Brookings 2015	15.8 (+3.0)	8.7 (+2.0)	18.6 (−0.8)	13.0 (−0.3)	25.1 (+0.1)	19.6 (+0.7)	27.3 (−0.5)	21.7 (+0.6)	25.1 (−1.6)	19.5 (−0.5)
Brookings 2016	13.8 (+1.0)	7.9 (+1.2)	20.8 (+1.4)	14.6 (+1.3)	27.3 (+2.3)	21.3 (+2.4)	27.1 (−0.7)	21.6 (+0.5)	26.3 (−0.4)	20.9 (+0.9)
Brookings 2017	13.2 (+0.5)	7.2 (+0.5)	19.4 (0.0)	13.2 (0.0)	26.1 (+1.1)	19.4 (+0.5)	28.9 (+1.1)	22.8 (+1.7)	23.3 (−3.4)	18.9 (−1.1)
Pierre 2015	17.7 (+2.1)	9.8 (+1.5)	19.3 (−1.8)	12.9 (−1.5)	27.1 (+0.4)	20.6 (+0.6)	30.9 (−0.8)	23.4 (−0.5)	30.0 (−0.6)	22.6 (−0.7)
Pierre 2016	15.8 (+0.2)	8.9 (+0.6)	22 (+0.9)	14.4 (0)	30.1 (+4.4)	22.2 (+2.2)	32.3 (+0.6)	24.4 (+0.5)	30.2 (+0.4)	22.7 (+0.6)

Table 3.
Maximum and average temperature throughout the crop growing period for camelina grown at Brookings and Pierre, SD in 2015, 2016 and 2017 (numbers in parentheses indicate deviations from 1981 to 2010 average).

	Height	Maturity	Seed yield	Oil conc	Oil yield	Lodging	Shatter
N Rate (kg ha^{-1})	(cm)	(days)	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	(1–9)	(%)
Brookings 2015							
0	73.2	109^{b}	1116^{b}	327^{a}	373	1.25	2.25
28	73.6	112^{a}	1360^{a}	258^{bc}	353	2.25	1.75
56	74.5	111^{a}	1397^{a}	275^{b}	388	2.75	1.25
84	78.6	113^{a}	1340^{a}	268^{b}	361	4.00	1.75
140	76.7	113^{a}	1455^{a}	226^{c}	332	4.75	1.00
Pierre, 2015							
0	79.2	110^{b}	1186	228^{a}	268^{a}	7.30	3.00
28	76.5	108^{b}	1353	188^{b}	254^{a}	8.00	3.00
56	84.8	111^{b}	1396	185^{b}	258^{a}	8.00	2.67
84	81.8	115^{ab}	1348	177^{b}	238^{ab}	9.00	2.33
140	76.2	116^{a}	1393	149^{c}	207^{b}	8.00	2.00

Within each column and location, means followed by the same letter are not significantly different at P< 0.05.

Table 4.
Nitrogen (N) fertilization rate effects on plant height, days to maturity, seed yield, oil concentration, oil yield, lodging and pod shatter in camelina grown at two locations in SD in 2015.

	Height	Seed yield	Oil concentration	Oil yield
N Rate (kg ha^{-1})	(cm)	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Brookings 2016				
0	68.7^{e}	988^{b}	350^{a}	345^{b}
28	74.7^{d}	1215^{b}	324^{a}	392^{ab}
56	77.7^{c}	1112^{b}	293^{b}	317^{b}
84	81.1^{b}	1197^{b}	321^{ab}	386^{ab}
140	88.2^{a}	1579^{a}	286^{b}	451^{a}
Pierre, 2016				
0	58.0^{d}	416^{d}	271^{a}	91^{b}
28	67.4^{c}	657^{c}	204^{a}	134^{a}
56	70.4^{bc}	723^{bc}	193^{ab}	139^{a}
84	71.7^{b}	770^{b}	176^{b}	135^{a}
140	75.4^{a}	817^{a}	138^{c}	113^{ab}

Within each column and location, means followed by the same letter are not significantly different at P< 0.05.

Table 5.
Nitrogen (N) fertilization rate effects on plant height, seed yield, oil concentration, and oil yield in camelina grown at two locations in SD in 2016.

to applied N to 200 kg ha^{-1} N although the response was different depending on genotype. Similarly, Mahli et al. [21] reported that maximum seed yield of camelina was achieved at an N rate of 170 kg ha^{-1} supporting the notion that camelina has a high demand for N. However, studies conducted in the US suggest that camelina has a lower N requirement. Wysocki et al., [19] reported that camelina seed yield in the Pacific Northwest was maximized between 44 and 88 kg ha^{-1} depending on location.

In a study conducted in Montana, Mohammed et al., [18] reported that application of 60 kg ha^{-1} N produced maximum agronomic seed and oil yield. In the current study, regression analysis showed that seed yield had a linear relationship with N rate at a higher yielding environment at Brookings while the relationship was quadratic at the lower yielding environment at Pierre (**Figure 1**). Other researchers have also shown similar results indicating different response of camelina to N rate depending on genotypes and environmental conditions. Wysocki et al. [19] reported camelina seed yield response to N rate varied widely from one location to the other depending on annual precipitation and soil available N. They reported linear increase in camelina seed yield with increase in N rate at locations with high precipitation and while locations with lower precipitation showed no response. Research conducted in Canada reported both linear and quadratic response depending on camelina genotype [22].

Seed oil concentration was significantly influenced by N rate at both locations and in both years (**Tables 4 and 5**). Seed oil concentration decreased at a rate of 0.40 to 0.60 g kg^{-1} for 1 kg ha^{-1} increase in N fertilizer rate at Brookings and at a

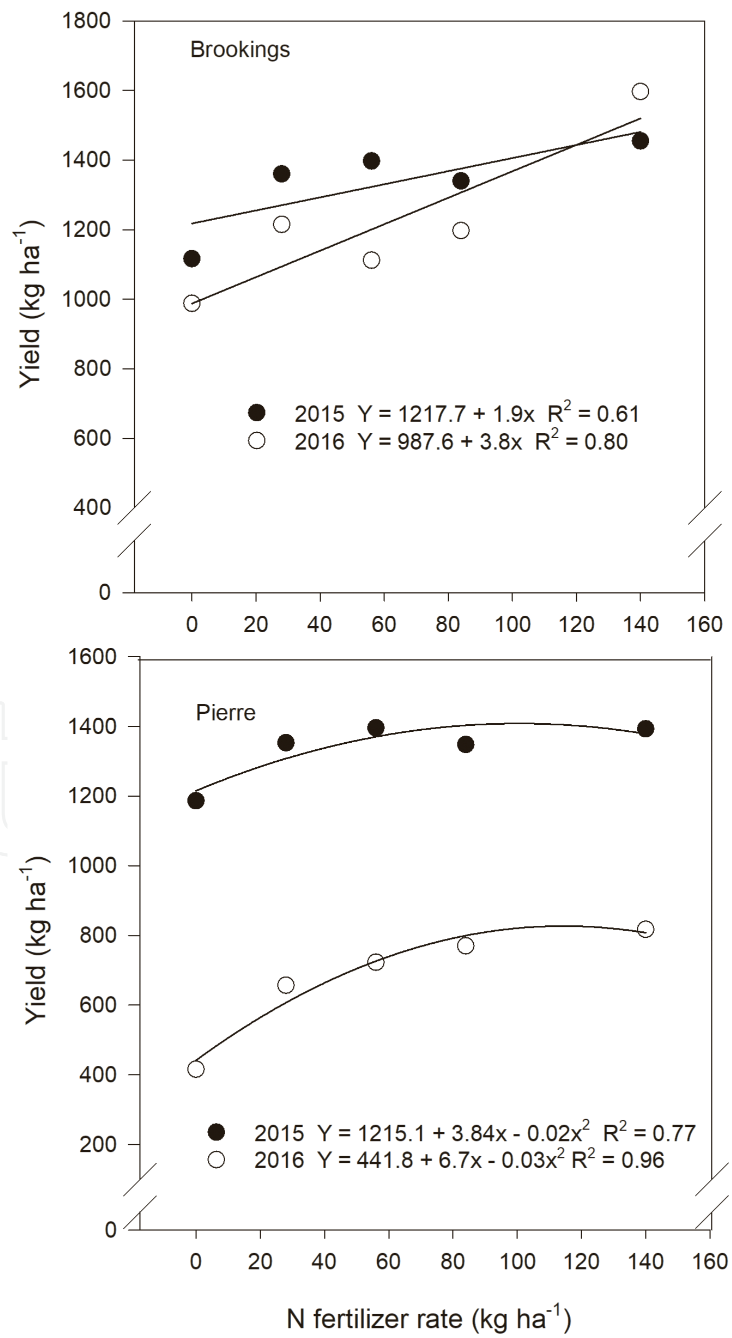

Figure 1.
Camelina seed yield as a function of nitrogen fertilization rate at Brookings and Pierre, SD in 2015 and 2016.

higher rate of 0.50 to 0.80 g kg^{-1} for 1 kg ha^{-1} increase in N fertilizer rate at Pierre (**Figure 2**). These findings agree with earlier findings which show seed oil concentration decreasing linearly in response to increasing N rate [18, 20, 21]. In both years and both locations, the control treatment had the greatest oil concentration while the lowest oil concentration was observed in the highest N rate of 140 kg N ha^{-1} (**Tables 4** and **5**) likely due to the dilution effect [18]. In addition, increased N availability to the plant results in protein formation at the expense of fatty acid synthesis due to competition during carbohydrate metabolism [32]. Location impacted oil concentration with seed from the wetter environment in Brookings showing greater oil concentrations than at Pierre and decreasing less with increase in N fertilizer rate. The low oil concentration at Pierre is most likely due to overall lower precipitation and higher temperature throughout the growing season. Accelerated growth

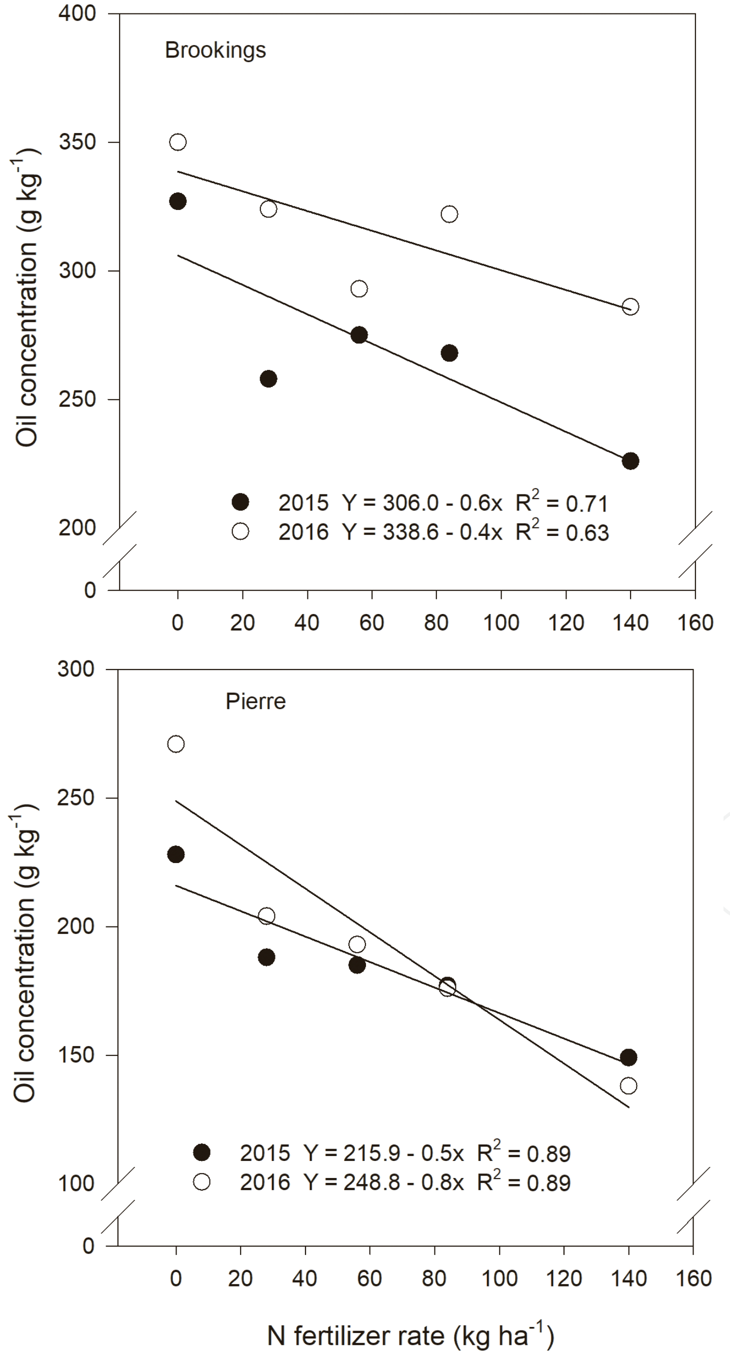

Figure 2.
Camelina seed oil concentration as a function of nitrogen fertilization rate at Brookings and Pierre, SD in 2015 and 2016.

and short growing seasons in semi-arid environments negatively impacts seed maturity and oil accumulation resulting in low seed oil concentrations [33].

Seed oil yield was significantly influenced by N rate at Pierre in 2015 and at both locations in 2016 (**Tables 4** and **5**). At Pierre in 2015, the highest N rate of 140 kg ha^{-1} had the lowest oil yield (207 kg ha^{-1}) while the greatest oil yield (268 kg ha-1) was recorded in the control treatment though this value was similar to oil yields obtained at N rates of 28 to 84 kg ha^{-1} (**Table 4**). The results were reversed in 2016 at Pierre, with the control treatment having significantly lower oil yield compared to all other N rates except the highest N rate of 140 kg ha^{-1} (**Table 5**). At Brookings on the other hand, the highest N rate of 140 kg ha^{-1} had the greatest oil yield (451 kg ha^{-1}) with this values significantly greater than the oil yield for the control treatment (345 kg ha^{-1}) but similar to intermediate N rates (**Table 5**). Oil yield was influenced by location, as the Brookings location produced greater average oil yields than the Pierre location, which resulted from greater seed oil concentration at Brookings in both years (**Tables 4** and **5**). Higher temperatures during seed filling have a negative effect on seed oil content [34, 35] explaining the lower oil yields at Pierre where temperatures were extremely high during the seed filling period.

3.3 Seeding rate effects

Plant population density increased with seeding rate at Brookings in 2016 and 2017 and at Pierre in 2016. At Brookings in 2016 and 2017, plant stand counts significantly increased with every seeding rate increase (**Tables 6** and **7**). At Pierre,

	Plant stand	Height	Pods	Seeds	Seed yield	Oil conc	Oil yield	Shatter
	plant m^{-2}	cm	plant^{1}	pod^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	%
Brookings 2016								
Seeding Rate (kg ha^{-1})								
4.5	394^{d}	84.7	77^{a}	13	1293^{a}	296	384	31.2^{a}
9	475^{c}	81.6	65^{b}	13	1160^{a}	301	345	29.4^{a}
13	638^{b}	83.2	63^{b}	11	1362^{a}	277	383	23.7^{b}
17.5	820^{a}	87.0	35^{c}	11	928^{b}	273	253	23.7^{b}
Varieties								
SO-40	584	83.7	61	12	1138	283	323	27.2
SO-50	580	84.5	59	11	1233	291	359	26.9
Pierre 2016								
Seeding Rate (kg ha^{-1})								
4.5	192^{c}	74.4^{a}	71	10	567^{b}	217	123	3.7
9	283^{b}	73.3^{a}	69	11	647^{ab}	203	131	6.2
13	339^{ab}	70.5^{b}	67	12	764^{a}	215	179	8.3
17.5	365^{a}	66.9^{c}	71	12	594^{b}	199	120	8.1
Varieties								
SO-40	296	71.3	55^{b}	11	607	192^{b}	117	5.7
SO-50	294	71.2	70^{a}	11	678	225^{a}	160	7.5

Within each column and location, means followed by the same letter are not significantly different at $P< 0.05$.

Table 6.
Seeding rate and camelina variety effects on plant height, pods per plant, seeds per pod, seed yield, oil concentration, oil yield and pod shatter in camelina grown at two locations in SD in 2016.

	Plant Stand	Height	Yield	Shatter
	plant m^{-2}	cm	kg ha^{-1}	%
Seeding Rate (kg ha^{-1})				
4.5	155^{d}	68.3	1214	32.5^{a}
9	193^{c}	68.1	1249	31.2^{a}
13	221^{b}	66.7	1190	27.5^{b}
17.5	293^{a}	69.5	1265	26.9^{b}
Varieties				
SO-40	216	68.3	1126^{b}	30
SO-50	215	68.1	1332^{a}	29.1

Within each column and location, means followed by the same letter are not significantly different at P< 0.05.

Table 7.
Seeding rate and camelina variety effects on plant height, seed yield, and pod shatter in camelina grown at Brookings, SD in 2017.

the lower two seeding rates of 4.5 and 9 kg ha^{-1} had similar plant stands with stands increasing significantly with each increase in seeding rate for the higher two seeding rates (**Table 6**). These findings agree with other reports [23, 25]. In 2016 average plant stand counts was greater in Brookings (582 plants m^{-2}) than in Pierre (295 plants m^{-2}). Plant stand counts were lowest in Brookings in 2017 (216 plant m^{-2}). The variation in stand counts between locations and years suggest emergence rates likely depend on environmental conditions and seed bed preparation which were inconsistent among environments. For example, at Brookings the study was conducted under conventional tillage making for a more favorable seedbed whereas in Pierre no till practices exposed seeds to a poorer seedbed.

Plant height was only significantly influenced by seeding rate at Pierre in 2016 likely due to lodging at the highest seeding rate of 17.5 kg ha^{-1}. Number of pods per plant and seeds per pod were measured at both locations only in 2016. At Brookings, number of pods per plant decreased with increasing seeding rate with the highest seeding rate of 17.5 kg ha^{-1} having a significantly lower number pods (35 pods per plant) compared to the lower three seeding rates. The lowest seeding rate of 4.5 kg ha^{-1} had the greatest number of pods (77 pods per plant). Similar to the current findings, Urbaniak et al. [25] reported a decrease in pods per plant with increasing seeding rate. The lack of change in pod number as seeding rate increased at Pierre is likely due to poor stand establishment resulting in lower plant populations at all seeding rates.

Seeding rate had a significant impact on seed yield at Brookings and Pierre in 2016 but seed yield was not affected by seeding rate at Brookings in 2017. At the Brookings location, the lower three seeding rates (4.5, 9 and 13 kg ha^{-1}) yielded the same and significantly greater than the highest seeding rate of 17.5 kg ha^{-1}. At a drier environment in Pierre, on the other hand, the greatest seed yield was obtained at a seeding rate of 13 kg ha^{-1} with this yield similar to the yield obtained with a seeding rate of 9 kg ha^{-1} but significantly greater than the yield obtained at the lowest seeding of 4.5 kg ha^{-1} and the highest seeding rate of 17.5 kg ha^{-1}. Other researchers have also reported inconsistent results on camelina seed yield response to seeding rate. Gesch et al. [23] reported no response to seeding rate and attributed the lack of response to plasticity of camelina and therefore the crop's ability to compensate for lower plant densities. While the current results agree with the above observation, our results further suggest this ability to compensate for lower plant densities is likely influenced by environmental conditions. We observed higher yield compensation ability of camelina at a higher yielding environment at Brookings compared to a harsher lower yielding environment at Pierre. Urbaniak et al. [25] reported that seeding rate strongly affected plant population but that seed yield response to seeding rate was weak. McVay and Khan [24] reported that a stand count reduction of 90% at the rosette stage only reduced seed yield by 19% supporting the above assertion that seed yield response to seeding rate is weak.

Seed oil concentration and oil yield were not influenced by seeding rate. This is similar to previous reports [23, 24]. We observed that lower plant populations due to lower seeding rate had a higher rates of pod shatter compared to higher seeding rates (**Tables 6** and 7). This suggests that increasing seeding rate can result in slight decreases in pod shatter. This association is difficult to explain since earlier reports [24] suggest that stand reduction at rosette stage of camelina delays plant maturity. Therefore, increasing seeding rate would be expected to reduce days maturity, thus increasing the period where mature pods are exposed to hot and dry conditions which promote shattering. However, plants in thin stands are more exposed the elements of wind thus causing more pod shatter. Pod shatter at Brookings in 2016 was slightly higher than in 2017 due to prolonged periods of late-season rains that delayed dry-down and harvest time resulting in increased prevalence of pod shatter.

The two camelina varieties used in the study performed the same for most measured traits except for number of pods per plant and seed oil concentration at Pierre in 2016 and seed yield at Brookings in 2017. The variety SO-50 outperformed SO-40 in all the three traits that were different between the two varieties.

4. Conclusion

These results show that although considered a low-input crop, camelina can respond positively to high N rates in high yielding environments as indicated by a linear response to N rate observed at a high yielding environment in Brookings. This suggests that camelina has a potential for incorporation into both low-input as well as high-input cropping systems of the NGP. However, camelina yields were much lower in a dry year in the lower yielding environment suggesting the crop is unlikely to be economically viable in such environments. High N rates had a negative impact on seed oil concentration. The seeding rate study showed that camelina had a weak response to seeding rates supporting the theory that the crop has a great capacity to compensate for yield at low plant densities. However, we also observed the yield compensation capacity is influenced by environmental conditions. Poor stand establishment under no-till or a dry seedbed can reduce plant densities limiting the plasticity of camelina plants. This suggests that higher seeding rates may be necessary to help compensate for reduced stand establishment in drier environments under no-till.

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Conflict of interest

The authors declared no conflict of interest.

Author details

Thandiwe Nleya[1*], Dwarika Bhattarai[1] and Phillip Alberti[2]

1 Agronomy, Horticulture and Plant Science Department, South Dakota State University, Brookings, South Dakota, USA

2 University of Illinois Extension, College of Agricultural, Consumer and Environmental Sciences, Freeport, Illinois, USA

*Address all correspondence to: thandiwe.nleya@sdstate.edu

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