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Nutrient Requirements of Camelina for Biodiesel Feedstock in Central Montana

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ABSTRACT

Camelina (*Camelina sativa* L. Crantz) shows potential to provide an alternative renewable energy source and enhance crop diversification in temperate semiarid regions. Information on the effect of N, P, K, and S on yield and quality of camelina for biodiesel feedstock in the northern Great Plains (NGP) of the United States is limited. The objective of this experiment was to determine the effects of the above nutrients on seed and oil yields, test weight, oil concentration and agronomic nitrogen use efficiency (ANUE) of camelina on a clay loam soil in central Montana. Results showed that fertilizer treatments significantly affected seed yield, oil concentration and oil yield of camelina. The seed and oil yields ranged from 677 to 1306 kg ha^{-1} and from 234 to 445 kg ha^{-1}, respectively. Although the highest seed and oil yields were obtained from the application of 134–22–22–28 kg ha^{-1} N–P_2O_5–K_2O–S, they were statistically in the same group with yields achieved from the application of only 45 kg ha^{-1} N. Application of P and S fertilizers increased camelina seed yield compared with the control treatment. There was no response to K fertilization. Simultaneous application of N and S did not show synergistic effects in enhancing ANUE. The ANUE reduced with increasing N application rates. From trend analysis, application of 60 kg ha^{-1} N produced agronomic maximum seed and oil yields. Therefore, optimizing camelina seed and oil yields production with regard to nutrient management using current variety should focus on N fertilization.

Core Ideas

- The responses of camelina seed and oil yields to nutrient applications were substantial compared with the control treatment.
- Trend analysis showed that camelina requires about 60 kg ha^{-1} N to achieve agronomic optimum seed and oil yields.
- This agronomic data will help policy makers, researchers, growers, and end users to make decision in the production and processing of camelina as energy crop.

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Camelina is an oilseed crop native to European countries (Matthäus and Zubr, 2000). It is well adapted to a wide range of environmental stresses and has shown better performance than canola (*Brassica napus* L.) in the NGP of the United States (McVay and Khan, 2011). Petroleum price instability, concern for global climate change and growing interest to diversify cereal dominated cropping systems in the NGP has triggered increased attention in research, production, processing, and marketing of camelina as an alternative renewable energy source.

Research indicates that camelina has very good characteristics as a biofuel feedstock including the ability to withstand low temperature and essential qualities for better engine performance (Bernardo et al., 2003; Pinzi et al., 2009; Shonnard et al., 2010). Oil from camelina seed dries fast making it suitable in the paint, varnish, and cosmetics industries (Zaleckas et al., 2012). In addition, seed and meal from camelina are rich in protein and thus can be used for animal feed (Wysocki et al., 2013). Besides these benefits, growing camelina in the cereal dominated dryland region will help to diversify cropping systems eventually contributing to system sustainability. Agronomic management practices for camelina production are limited. Therefore, to realize these advantages of growing camelina, improved agronomic management practices that can contribute to yield increase with improved quality are needed. This eventually will contribute to enhanced economic return for camelina growers and green energy production.

Different experiments have shown that camelina can be grown in dryland cropping systems (Jackson, 2008; McVay and Khan, 2011; Wysocki et al., 2013). Several research results revealed that application of balanced nutrients to oilseed crops increased yield and improved quality (Lanier et al., 2005; Rathke et al., 2005; Taylor et al., 2005; Pageau et al., 2006; Abbadi et al., 2008; Morshedi, 2011; Xie et al., 2015). Various responses to nutrient application from oilseed crops have been recorded likely due to spatial and temporal variability of the testing environments in terms of climatic and edaphic factors thus requiring site and crop specific nutrient recommendations.

Previous research results recommended from 78 to 100 kg ha^{-1} N for camelina production (Jackson, 2008). Nutrient requirement study results from the Pacific Northwest of the United States recommended 12 kg ha^{-1} N per 100 kg of expected grain yield to achieve optimum yield (Wysocki et

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Abbreviations: ANUE, agronomic nitrogen use efficiency; NGP, northern Great Plains.

al., 2013). Another fertility evaluation on camelina reported quadratic response to N fertilizer application (Johnson and Gesch, 2013). According to Zubr (1997), the N requirement of camelina can reach to the extent of 100 kg ha^{-1} depending on the soil fertility, the residual level of nutrients, and weather conditions. The yield of camelina had been shown to increase with increasing N rates (Agegenehu and Honermeier, 1997; Urbaniak et al., 2008). Increasing N levels from 60 to 130 kg ha^{-1} resulted in a 30% yield increase but decreased oil concentration (Agegenehu and Honermeier, 1997). These results reveal a wide range of responses to N fertilizer application signifying the need to have site specific recommendations for camelina production thus justifying the importance of this study.

Similarly, responses from P, K, and S fertilization of oilseed crops such as soya bean [*Glycine max* (L.) Merr.] are becoming extensive in the Midwest of the United States due to nutrient depletion. Previous studies have shown the importance of applying P and K fertilizer for oilseed crops (Jackson, 1999; Cheema et al., 2001). Sulfur deficiency and thus response to S fertilization is becoming more widespread mainly as a result of decreased atmospheric S inputs (Mahler and Maples, 1986; Jackson, 2000). Additionally, a study by Rasmussen et al. (1975) in Oregon showed that response to N fertilization was improved by S application. Sulfur is necessary for plant growth and physiological functions including chlorophyll formation, protein and vitamin development, and resistance to cold and water stress (Gardner et al., 2003). Sulfur deficiency may limit acetyl-CoA carboxylase activity, leading to the reduction of oil biosynthesis in oilseed crops (Ahmad et al., 2000). Therefore, providing sufficient S to growing camelina is essential.

Improved camelina varieties may require greater amounts of nutrients compared with older varieties. Moreover, longtime cropping in the NGP of the United States can result in nutrient depletion and imbalance, thus limiting seed and oil yields of camelina. Although camelina is considered a low input crop, research shows that nutrient application for other low input crops, such as switchgrass, increased biomass yield (Mohammed et al., 2015b). The same is likely true of camelina. Application of balanced nutrition is essential because it helps to optimize the efficient use of nutrients according to plant needs (Ezui et al., 2016). Information from research results that simultaneously assessed the effect of N, P, K, and S on seed yield, test weight, oil concentration, and oil yield of camelina is limited.

We hypothesized that the simultaneous application of a combination of nutrients will enhance seed yield, test weight, oil concentration, and oil yield of this newly emerging energy crop. Therefore, the objective of this experiment was to determine the effect of N, P, K, and S application on seed and oil yields, test weight, oil concentration, and agronomic N use efficiency of camelina for bioenergy feedstock.

MATERIALS AND METHODS

Site Description

The experiment was performed at the Central Agricultural Research Center (47°03′ N, 109°57′ W, 1400 m above sea level) near Moccasin and at Pendroy (48°04′ N 112°17′ W, 1302 m above sea level) Montana, from 2013 to 2015. The soil at Moccasin is classified as a Judith clay loam (fine-loamy, carbonatic, frigid Typic Calciustoll) and Scobey clay loam (fine, smectitic, frigid Aridic Argiustoll) at Pendroy. Before planting, composite soil samples were taken on the first week of April each year from 0- to 0.15-m and 0.15- to 0.30-m soil depths.

These soil samples were air dried and ground to pass through a 2-mm mesh sieve. Soil pH measured with pH electrode on a 1:1 of soil/water suspension. Soil ammonium and nitrate-N were extracted with 1.0 mol L^{-1} KCl. Ammonium N was measured using a Timberline ammonium analyzer (model TL-2800) (Timberline Instrument, Inc., Boulder, CO) and nitrate-N was determined following the cadmium reduction method. Available soil P was determined after extracting the soil with sodium bicarbonate (Olsen and Sommers, 1982). Potassium was extracted with ammonium acetate and determined with an Atomic Absorption Spectro Photometer (model 2380) (PerkinElmer, Billerica, MA). Sulfate-S was extracted with 1.0 mol L^{-1} KCl and measured using the turbidometric method (Bardsley and Lancaster, 1960). Soil total N and C content were measured by combustion method using an Elementar Vario Max analyzer (Vario MAX cube, Hanau, Germany).

Soil test results for the experimental sites show that mean soil pH was >7 for both locations (Table 1). The organic C and total N contents at the Pendroy site were more than the Moccasin site. Both locations had relatively high soil P and K content. The mean soil test results for each locations are presented in Table 1.

Both locations are considered temperate semiarid and monthly precipitation during the growing period (April–August) from 2013 to 2015 is shown in Table 2. Precipitation data were obtained from the Central Agricultural Research Center of Montana State University for the Moccasin site, and data from the USDA Natural Resource Conservation Service located at the Conrad Agricultural Research Center (site number 2117) were used for the Pendroy site. During the 3-yr study (2013–2015), Moccasin received higher precipitation than Pendroy except for the months of April and June of 2014 (Table 2). A little more than 52% of the precipitation in 2014 for the Moccasin site was received in August (mainly 23 and 24 Aug. 2014). Late August precipitation did not contribute to camelina growth and seed production since it was harvested 20 Aug. 2014. Therefore, although the total precipitation was high in 2014, its contribution to seed production was limited.

Experimental and Treatment Design

The experimental design was randomized complete block with four replications. There were 13 treatments (Table 3) including four levels of N (0, 45, 90, and 134 kg ha^{-1} N), two levels of P (0 and 22 kg ha^{-1} P_2O_5), two levels of K (0 and 22 kg ha^{-1} K_2O) and three levels of S (0, 11, and 28 kg ha^{-1} S). Urea, triple super phosphate, potassium chloride, and elemental S were the sources of N, P, K, and S, respectively. Ammonium sulfate and elemental S are common sources of S fertilizer in the area. However, to avoid confounding effects particularly when N rate was zero, elemental S was used as source of S since ammonium sulfate contains N. Farmers in the area also used elemental S as sources of S fertilization. However, solubility and availability of S from elemental S source may vary compared with ammonium sulfate to become plant available. Therefore, this S source need further investigation. Based on past experience, drilling N fertilizer at higher N

Table 1. Mean values of selected soil properties from background soil samples collected in the first week of April just before seeding from Moccasin and Pendroy, MT.

Soil properties	Location/soil depth, m			
	Moccasin		Pendroy	
	0.00–0.15	0.15–0.30	0.00–0.15	0.15–0.30
pH in 1:1 water	7.0	7.3	7.7	7.6
Organic C, g kg^{-1}	18	17	24	19
Total N, g kg^{-1}	1.78	1.70	1.95	1.85
Olsen P, mg kg^{-1}	24	16	65	47
K, mg kg^{-1}	386	337	428	303
S, mg kg^{-1}	11	4	6	7
Ammonium N, mg kg^{-1}	13.4	17.7	9.6	10.2
Nitrate-N, mg kg^{-1}	6.5	8.5	4.0	6.5

Table 2. Monthly precipitation (April–August in millimeters) from 2013 to 2015 at Moccasin and Pendroy, MT.

Location	Month	Year/precipitation		
		2013	2014	2015
		mm		
Moccasin	April	18	16	38
	May	81	42	96
	June	96	62	45
	July	43	35	45
	August	25	171†	14
	Total	263	325	237
Pendroy	April	18	41	3
	May	71	15	51
	June	71	81	15
	July	13	18	15
	August	30	53	20
	Total	203	208	104

† This precipitation was received after harvest.

rate together with the seed caused seedling injury (particularly when fertilizers are drilled into the same row and depth seed) evidenced from low number of seedling counts per m^2 compared to the control (unfertilized plots). Seedling injury can be avoided with band placement of fertilizer applications while seeding but requires special equipment. Therefore, all fertilizers were broadcasted by hand 2 wk after seed germination to avoid seed germination and seedling injury.

Trial Management and Data Collection

The trial was planted into tilled soil following winter wheat (*Triticum aestivium* L.) each year. The land was sweep tilled about 0.10-m deep in autumn and cultivated with a spike tooth harrow in spring to smooth the seedbed. Glyphosate [*N*-(phosphonomethyl) glycine] (Syngenta Crop Protection, Inc. Greensboro, NC) was sprayed at 1.1 L a.i. ha^{-1} with 150 L H_2O ha^{-1} in fall and also in spring before planting. The spring camelina (cultivar Suneson) was planted at a seed

Table 3. Detail description of treatments with various combination of different levels of N, P, K, and S.

Treatment no.	Nutrient combination	N	P (P_2O_5)	K (K_2O)	S
		kg ha^{-1}			
T1	0N0P0K0S	0	0	0	0
T2	0N0P0K11S	0	0	0	11
T3	0N22P0K0S	0	22	0	0
T4	0N22P22K0S	0	22	22	0
T5	134N22P22K28S	134	22	22	28
T6	45N0P0K0S	45	0	0	0
T7	45N0P0K28S	45	0	0	28
T8	45N0P22K0S	45	0	22	0
T9	45N0P22K28S	45	0	22	28
T10	45N22P22K0S	45	22	22	0
T11	45N22P0K28S	45	22	0	28
T12	45N22P22K28S	45	22	22	28
T13	90N22P22K28S	90	22	22	28

rate of 5.6 kg ha^{-1} about 1-cm deep in the first week of April each year using a locally made hoe drill. The plot size was 1.5 by 6.1 m with 0.30 m row spacing. In mid-May, Assure II {Quizalofop P-ethyl ethyl-2-[4-(6-chloroquinoxalin-2-yloxy)-phenoxy] propionate} (DuPont, Wilmington, DE) was sprayed at 0.9 L a.i. ha^{-1} with 150 L H_2O ha^{-1} to control grass weeds at the Moccasin site only. The trial was harvested with a plot combine harvester in early August each year (Wintersteiger, Salt Lake City, UT). The operating specification of this combine harvester indicated for canola was used for camelina with little adjustment based on observations (degree of threshing and extent of seed loss with the straw) using border plots. Some chaffs were collected with the seeds while harvesting camelina with the combine harvester (combine fan speed was kept low to avoid seed loss) which required additional seed cleaning in the laboratory to remove the chaffs using a sieve with 3 mm diam. opening. But in 2015, grain yield was calculated from a net plot of 1 m^2 harvested by hand using a hand-held sickle.

The grain moisture content and test weight were determined simultaneously with a grain moisture tester (GAC 2100) (AgriMart, Owensboro, KY). Then, seed yield was adjusted to 8% moisture content before running statistical analysis. Camelina seed oil content was determined using Perten Diode Array DA 7200 near-infrared reflectance (NIR) analyzer (Perten Instruments, Hägersten, Sweden) (McVay and Khan, 2011). Camelina oil yield was calculated by multiplying seed oil concertation by seed yield. Agronomic N use efficiency was calculated as the difference between yield from fertilized plots and yield from the control treatment (no fertilizer) and then dividing this result by the amount of N fertilizer applied. ANUE was calculated from mean values and not statistically analyzed.

Statistical Analysis

Homogeneity of variance and normality of data distribution were tested following the Levene procedure (Levene, 1960) and Proc Univariate of SAS, respectively, (SAS Institute, 2001). The effect of treatments, locations, years, and their interaction were analyzed with PROC GLM of SAS software. We found that treatment × year and treatment × location interaction effects were not significant for seed and oil yields. Therefore, the effect of treatments (combined over years and locations) from analysis of variance outputs are presented and discussed. But these factors had interactive effects on test weight and oil concentration. The effects of locations and years as main factors are also presented and discussed. When ANOVA showed significant differences ($P < 0.05$), then, treatment means were separated with Tukey's Honestly Significant Difference (HSD) at $P = 0.05$. Tukey's HSD is a powerful pairwise mean separation method since it helps the researcher avoid a type I error (McHugh, 2011). The General linear model of SAS was used to test trend analysis (linear, quadratic, and cubic) for N rates (0, 45, 90, and 134 kg ha^{-1} N) at constant (22–22–28 kg ha^{-1} P_2O_5–K_2O–S) application rates on seed and oil yields and oil concentration of camelina. In this trend analysis, the 0 kg ha^{-1} N was the control treatment without any fertilization.

RESULTS AND DISCUSSION

Seed Yield

The effects of treatment application and year on camelina seed yield were very highly significant ($P < 0.0001$) but location or treatment × location or treatment × year interaction effects were not significant (Table 4). Averaged over years and locations, mean camelina seed yield ranged from 677 to 1360 kg ha^{-1} (Table 5). Mean camelina seed yield increased by 93% with the application of 134–22–22–28 kg ha^{-1} N–P_2O_5–K_2O–S compared with the control treatment (Table 5). However, the difference in mean camelina seed yield between 134 and 22–22–28 kg ha^{-1} and 45–0–0–0 kg ha^{-1} N–P_2O_5–K_2O–S was not statistically significant. As shown in Table 5, application of any one of the nutrients alone led to increased camelina seed yield compared to the unfertilized control, indicating that camelina is responsive to fertilization. These results show that even if camelina is considered as low input crop, it needs a modest amount of N fertilization to optimize yields. Solis et al. (2013) reported that under N deficiency, camelina has small and greenish yellow leaves; it matures earlier with fewer silicles and smaller seeds compared with plants receiving sufficient N. This is in agreement with our observations and results.

Trend analysis for N rates indicated that the linear and quadratic components were significant for seed yield (Table 4). Based on this analysis, 60 kg ha^{-1} N application looks reasonable to achieve agronomically optimum camelina seed yield as shown in Fig. 1. This rate is very close to the previous rate (78–100 kg N ha^{-1}) recommended for camelina production in similar environments (Jackson, 2008).

Nitrogen use efficiency is an important index in optimizing N use from economic and environmental perspectives. Agronomic N use efficiency is widely used as a criteria to

Table 4. Analysis of variance table for treatments, locations, years, and their interactions and trend analysis for N rates showing *F* and *P* values effects on seed yield, test weight, oil concentration, and oil yield of camelina. Replication and other interactions effects were included in the model but not shown in this table since they are not relevant.

Source of variation	Seed yield		Test weight		Oil concentration		Oil yield	
	F value	*P* > *F*	*F* value	*P* > *F*	*F* value	*P* > *F*	*F* value	*P* > *F*
Treatment (Trt)	4.93	<0.0001	1.53	0.1235	3.05	0.0005	3.46	0.0001
Location	0.26	0.6130	52.78	<0.0001	1.42	0.2348	0.80	0.3717
Year	12.90	<0.0001	206.76	<0.0001	495.60	<0.0001	3.37	0.0360
Trt × location	0.52	0.9033	1.97	0.0328	1.04	0.4120	0.50	0.9150
Trt × year	0.78	0.7550	1.30	0.0965	1.71	0.0234	0.76	0.7855
Trend analysis for N rates								
Linear	16.43	0.0001	0.54	0.4657	0.46	0.4997	11.50	0.0011
Quadratic	11.36	0.0012	0.32	0.5774	0.37	0.5460	6.60	0.0119
Cubic	3.97	0.0498	2.04	0.1602	0.73	0.3958	1.46	0.2303

Table 5. Mean seed yield, test weight, oil concertation and oil yield of camelina for the different treatments when results combined over locations (Moccasin and Pendroy, MT) and years (2013–2015).

Treatment number	Nutrient combination	Seed yield	Test weight	Oil concentration	Oil yield
		kg ha^{-1}	kg hL^{-1}	g kg^{-1}	kg ha^{-1}
T1	0N0P0K0S	677d†	66.0	346bcd	234c
T2	0N0P0K11S	1069bc	66.0	353abc	377abc
T3	0N22P0K0S	1032c	66.0	352abcd	363bc
T4	0N22P22K0S	1073bc	66.1	359a	386abc
T5	134N22P22K28S	1306a	66.0	341d	445a
T6	45N0P0K0S	1190abc	66.2	344cd	409ab
T7	45N0P0K28S	1095abc	66.0	357ab	391ab
T8	45N0P22K0S	1230abc	66.0	352abcd	433ab
T9	45N0P22K28S	1245ab	66.3	348abcd	433ab
T10	45N22P22K0S	1249ab	66.1	350abcd	437ab
T11	45N22P0K28S	1258ab	66.0	347abcd	436ab
T12	45N22P22K28S	1235abc	66.2	343cd	424ab
T13	90N22P22K28S	1278ab	66.2	342cd	437ab

† Means followed by a common letter in a column are not significantly different from each other at $P = 0.05$.

evaluate N use efficiency in relation to N fertilizer use and management. We evaluated the change in ANUE with increasing N rates and also with and without S application to see the potential economic and environmental benefits of fertilization. Generally, agronomic management practices with higher ANUE value will increase net returns to investment and are safe to environments. The highest ANUE (data not shown but it can be calculated from Table 5) was for the application of 45–22–0–28 kg ha^{-1} N–P_2O_5–K_2O–S. Application of this treatment produced 12.9 kg of camelina seed for each kg of N fertilizer applied. ANUE were 12.4, 6.7, and 4.7 when N was applied at 45, 90, and 134 kg ha^{-1} N, respectively. The decrease of ANUE with increasing N fertilizer application rates is a common phenomenon and it is consistent with previous findings for other crops such as wheat (Mohammed et al., 2013).

The ANUE was higher (ANUE = 11.4) when N was applied without S fertilization (45–0–0–0 kg ha^{-1} N–P_2O_5–K_2O–S) than with S (45–0–0–28 kg ha^{-1} N–P_2O_5–K_2O–S) (ANUE = 9.3). However, previous research has reported a synergistic effect between N and S fertilizer applications (Rasmussen et al., 1975; Jackson, 2000). Sulfur and N have strong interactions for crop growth and quality because of their mutual requirement for amino acids (Jamal et al., 2010). Application of high N rates can create S deficiency because N increases the utilization of S in plants (Jamal et al., 2010). For instance, synergistic effects of N and S fertilizers were observed in the uptake of these nutrients by maize (*Zea mays* L.) and rapeseed (*Brassica campestris* L.) (Fazli et al., 2008). According to Janzen and Bettany (1984), an increase in N when S is insufficient would accentuate the shortage of S and lead to lower yields. The absence of a synergistic effect of N and S for ANUE

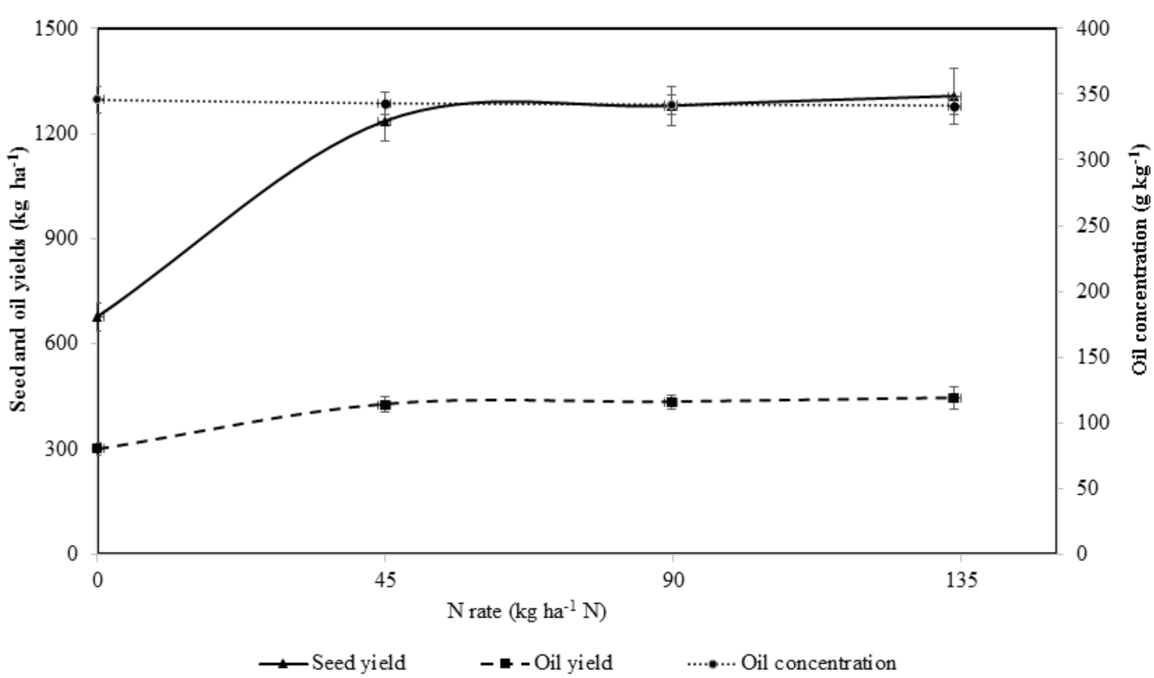

Fig. 1. Trend analysis showing the effect of N rates on seed and oil yields and oil concentration of camelina when data combined over locations and years. Error bars are standard error of the means (*n* = 24).

in our study may be related to the N/S ratio in the soil besides differences in environments, crops, and varieties. In addition, the elemental S might have not been oxidized sufficiently to provide enough S to growing plant. This needs detailed investigation taking different S fertilizer sources, soil, and climatic factors into account.

Phosphorus and S fertilizer application increased camelina seed yield compared with the control treatment (Table 5). Camelina seed yield increased by 52 and 58% over the control treatment with the application of 22 and 11 kg ha^{-1} of P_2O_5 and S, respectively, (Table 5). These responses to P and S fertilizer application were not observed in the previous study (Jackson, 2008). Sulfur application improves plant growth because S is a cofactor in proteolytic enzymes and S is essential in the synthesis of some vitamins (Solis et al., 2013). Potassium fertilization did not show any significant seed yield advantage perhaps due to the presence of sufficient available K initially present in the soil (Table 1). However, for a similar soil K test result in the same region, Jackson (1999) recommended from 17 to 34 kg ha^{-1} of K_2O for canola production in Montana. Usually when production information is not available for camelina, those agronomic practices recommended for canola are used. But this result indicates that canola may require more K than camelina and shows the need for crop specific nutrient recommendations for a given area.

Averaged across years, the seed yields of camelina from Pendroy and Moccasin were statistically the same (Table 6). But significant seed yield difference was found among years (Table 7). The seed yields were higher in 2013 compared with 2014 and 2015 (Table 7) and might be related to variation in precipitation amount and distribution between these years. For instance, the total precipitation in 2014 was relatively higher than 2013 and 2015 for both locations (Table 2). However, relative seed yield in 2014 was lower than 2013. In addition, the lower total precipitation received in May, June, and July of 2014 than 2013 (Table 2) may explain why the relative yield in 2014 was lower than 2013. The amount and distribution of precipitation between May and July likely contributed the most to differences in growth and yield between years. The variation in inter-seasonal precipitation amount and distribution affecting biomass and grain yields, and response to N fertilizer application has been shown in other studies (Mohammed et al., 2014, 2015a, 2015b). Interestingly, the difference in precipitation received between years was substantial but camelina seed yield difference between years was not. The absence of this yield tradeoff may indicate that agronomically camelina is a good fit to diversify cereal dominated dryland cropping systems, where low precipitation is a major limiting factor for crop production.

Test Weight

The effects of location, year and treatment × location interaction were significant on test weight but treatment application was not significant (Table 4). The absence of test weight increase due to fertilization application in our study is contrary to Solis et al. (2013) findings and needs further investigation. However, Simón et al. (2002) reported no increase in test weight and thousand kernel weight in wheat due to N fertilizer. The mean test weight for Pendroy was higher than Moccasin (Table 6). Also, mean test weight was significantly higher in 2013 than 2014 (Table 7). Availability of soil water during seed formation and development is essential for increased test weight since it increases seed plumpness. In the present study, precipitation received in June and July may explain the higher test weight in 2013 than 2014. But this needs further research since camelina grown at Pendroy had greater test weight compared with Moccasin despite receiving less precipitation. Uniform and big seed size is important in the oil extraction processes because it helps to optimize production resources while crushing the seeds. When test weight is low due to small seed size and/or weight, it will challenge the mechanical crushing process for oil seeds and sometimes smaller seed slides in between the belts resulting seed loss and wastage. Camelina seed with higher test weight may have an advantage for the crushing industry over seed with low test weight.

Oil Concentration

Treatment and year affected camelina seed oil concentration (Table 4). Maximum oil concentration (359 g kg^{-1}) was achieved from the application of 0–22–22–0 kg ha^{-1} N–P_2O_5–K_2O–S compared with other treatments (Table 5). The effect of N application on oil concentration was not significant, and although there was a tendency to slightly decrease with increasing N rates

Table 6. Mean seed yield, test weight, oil concentration and oil yield of camelina at Moccasin and Pendroy (combined over years), Montana.

Location	Seed yield	Test weight	Oil concentration	Oil yield
	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	kg ha^{-1}
Moccasin	1112	65.8b†	357	397
Pendroy	1183	66.4a	341	403

† Means followed by a common letter in a column are not significantly different from each other at $P = 0.05$.

Table 7. Mean seed yield, test weight, oil concentration and oil yield of camelina in 2013, 2014, and 2015 when combined over locations (Moccasin and Pendroy) in Montana.

Year	Seed yield	Test weight	Oil concentration	Oil yield
	kg ha^{-1}	kg hL^{-1}	g kg^{-1}	kg ha^{-1}
2013	1288a†	68.0a	296b	381b
2014	1045b	65.3b	373a	390ab
2015	1110b	nd‡	377a	418a

† Means followed by a common letter in a column are not significantly different from each other at $P = 0.05$.

‡ nd = no data.

(Fig. 1). This is in agreement with other findings (Agegenehu and Honermeier, 1997). Moreover, a similar study on flax (*Linum usitatissimum* L.) indicated an insignificant effect of N fertilization on seed oil concentration (Xie et al., 2015).

The lowest oil concentration was from the fertilizer treatment with highest seed yield (Table 5). This might be due to a dilution effect and similar trends have been reported for other crops (Mohammed et al., 2013; Xie et al., 2015). In addition, Rathke et al. (2005) explained that increased N fertility results in increased protein formation at the expense of fatty acid synthesis due to their competition for carbon skeletons during carbohydrate metabolism. The oil concentration in 2013 was lower than 2014 and 2015 probably due to dilution effect and environmental factors such as weather mainly precipitation and temperature.

Seed Oil Yield

The effect of treatment application and year resulted in significant difference in oil yield (Table 4). The highest oil yield (445 kg ha^{-1}) was recorded from the application of 134–22–22–28 kg ha^{-1} N–P_2O_5–K_2O–S. This oil yield was 90% higher than the control treatment. Trend analysis results showed that the linear and quadratic components were significant for N rates (Table 4). Similar to seed yield, the oil yield difference between the 134–22–22–28 kg ha^{-1} and 45–0–0–0 kg ha^{-1} N–P_2O_5–K_2O–S treatments was not significant. The oil yield was higher in 2015 than 2013, which resulted from greater seed oil content in 2015 (Table 7). Oil yield is very important since the final objective of growing camelina as a biofuel feedstock is to provide oil for biodiesel. Therefore, the above 90% oil yield increase due to fertilization can be used as an optional strategy to enhance renewable energy production from camelina.

CONCLUSION

This study revealed that although the highest seed and oil yields of camelina could be achieved with the application of 134–22–22–28 kg ha^{-1} N–P_2O_5–K_2O–S, they were not statistically different than those obtained from the application of 45 kg ha^{-1} N alone. Phosphorus and S fertilization increased seed yield compared with the control treatment but these responses were not significantly different from the 45–0–0–0 kg ha^{-1} N–P_2O_5–K_2O–S application. The result demonstrated absence of synergistic effect of N and S fertilization in seed yield response. This needs further investigation considering the short growing season and slow availability of S from elemental S fertilizer. It is our suggestion that applying small amounts of P and S, at about 10 kg ha^{-1} each may help to minimize nutrient depletion (for soil fertility maintenance purpose). Potassium fertilization did not show any significant yield advantage probably due to high soil available K initially present in the soil. This study showed absence of synergistic effect of N and S fertilizer applications with regard to enhancing ANUE of camelina as well. The ANUE reduced with increasing N rates. Based on trend analysis, application of 60 kg ha^{-1} N resulted in agronomic optimum camelina seed and oil yields in central Montana. Therefore, optimizing camelina seed and oil yields for biofuel feedstock production with regard to nutrient management using the current camelina variety should focus mainly on N fertilization.

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