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Evaluating Agronomic Responses of Camelina to Seeding Date under Rain-Fed Conditions

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ABSTRACT

The potential to use camelina (*Camelina sativa* L.) as a bioenergy crop has increased the need to develop management practices that would improve sustainable production. This study evaluated the effects by cultivars (Blaine Creek, Pronghorn, and Shoshone) and three spring seeding dates on the performance of camelina grown under rain-fed conditions in northern Wyoming. Results showed significant effects of cultivar and/or seeding dates on camelina establishment, phenology, yield, seed protein, oil content, and estimated biodiesel yield. Growing degree-day (GDD) requirements for plant emergence, flowering, and maturity were 34, 417, and 998, respectively. Among the three cultivars studied, Blaine Creek and Pronghorn had better establishment and subsequent seed yield in both years. Averaged across the 2 yr, seed yield of Blaine Creek and Pronghorn were 931 and 963 kg ha^{-1}, respectively, greater than that of Shoshone (826 kg ha^{-1}). Seeding date had no effect on seed yield in 2013. However, in 2014, early seeding increased camelina seed yield. Early seeding in 2014 resulted in a general increase in plant height, harvest index, protein yield, oil content, and estimated biodiesel yield, but reduced protein content. Our findings showed seeding camelina early resulted in good plant establishment, increased seed yield, oil content, and the estimated biodiesel yield. Nonetheless, early seeding could be restrained by wet field conditions prevalent in the spring in most regions of the Great Plains. Hard frost can also be problematic for young spring camelina seedlings.

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Camelina is an ancient crop believed to have evolved as a weed in fields planted with flax, hence the name “false flax” (Budin et al., 1995; Gugel and Falk, 2006). According to Matthäus and Zubr (2000), camelina was cultivated for oil in Europe during the Bronze and Iron Ages; however, its production dwindled during the Middle Ages. There has been recent interest in camelina production because of increased demand for biofuel and other industrial applications from non-edible oilseeds. Several attractive features of camelina make it a potential oilseed crop. It is a low-cost bioenergy crop and the oil has been used successfully as fuel for diesel transport engines (Bernardo et al., 2003). According to Shonnard et al. (2010), when camelina jet fuel was flight tested, it met all the requirements for engine performance. In addition, greenhouse gases emitted during combustion of camelina-based fuels were lower than that of petroleum based fuel. Pinzi et al. (2009) indicated that cold weather affects the performance of most biofuels; however, fuel derived from camelina is able to withstand lower temperatures because of its high polyunsaturated fatty acid content. Besides biodiesel potential, camelina seeds have an average oil content of 350 to 450 g kg^{-1}, and the proportion of unsaturated fatty acid in the oil is approximately 900 g kg^{-1} (Gugel and Falk, 2006). The high content of unsaturated fatty acid makes camelina oil fast-drying which is useful for making environmentally friendly polymers, varnishes, paints, cosmetics, and dermatological products (Zaleckas et al., 2012).

Agronomically, camelina has wide environmental adaptation because it can grow under different climatic and soil conditions (Zubr, 2003). According to Moser and Vaughn (2010), camelina is able to grow well in semiarid regions and in low-fertile and saline soils. Camelina requires low agricultural inputs and its production cost is relatively low (Budin et al., 1995; Moser and Vaughn, 2010). Though camelina fits well in crop production systems in the semiarid regions in the Great Plains, there

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Abbreviations: DAP, days after planting; DOY, day of year; GDD, growing degree-days.

are limited production recommendations for camelina in the region. This suggests the need for information on management practices such as seeding dates, nutrient requirements, seeding rates, weed control, and best cultivars for specific locations to improve sustainable production.

Seeding date is an important management practice that could be adapted to minimize the adverse effects of late frost, moisture stress, and high temperature effects during critical stages of crop growth. Nevertheless, frosts in early spring pose potential threats to crop growth and development. This is typical for regions with variable weather conditions such as northern Wyoming that usually experience temperatures below 0°C in March through early May. Allen et al. (2014) indicated that camelina can perform well even at temperatures below 0°C; however, limited field access as a result of wet soil conditions can still impede early seeding.

Researchers have reported varying effects of seeding dates on camelina growth and seed production under rain-fed conditions. These discrepancies in the literature may be due to varying site-specific environmental conditions and edaphic factors. Berti et al. (2011) observed significant effects of seeding dates on plant growth and yield of camelina cultivated on five locations in Chile. Conversely, Urbaniak et al. (2008) did not observe any impact of seeding dates on plant emergence, height, yield, or oil content of camelina grown in the Atlantic region of Canada. Conceptually, early seeding is generally a good practice. However, for a short-season crop such as camelina (85–100 d; McVay and Lamb, 2008), the crop might be able to compensate for slight delays in seeding without any significant impact on growth, yield, and quality by completing its life cycle before the usual summer drought periods, depending on the type of cultivar used.

Crop cultivars differ in their absorption and translocation of soil moisture, plant nutrients, photosynthates, and most importantly, interactions with environmental factors. In addition, crop cultivars tolerate extreme temperatures, drought, and toxicity and deficiency of some nutrients differently due to genetic variability (Baligar et al., 2001). Camelina cultivars were reported to differ in their response to temperature (Allen et al., 2014) and nutrient assimilation (Jiang et al., 2013; Fujita et al., 2014). It would therefore be beneficial for growers to identify camelina cultivars that will perform well in a specific location. The objective of this study was to evaluate the effects of cultivar and three spring-seeding dates on the growth, yield, seed protein, and oil content of camelina for the environmental conditions of northern Wyoming.

MATERIALS AND METHODS

Experimental Site

The field experiment was conducted at the Sheridan Research and Extension Center (ShREC), University of Wyoming, 15 km west of Sheridan, WY (44°48′48″ N, 106°46′26″ W, 1154 m elevation). The soil at the experimental site was a Wyarno series (fine, smectitic, mesic Ustic Haplargid), characterized as very deep well drained, <0.5% slope, clay loam (31% sand, 36% silt, and 33% clay). Soil samples collected in the top 0 to 15 cm in 2013 and 2014 were analyzed for soil chemical properties (at Olsen's Agricultural Laboratory, Inc., McCook, NE) following standard soil test procedures. Soil pH (6.7 and 7.2); organic matter (2.2 and 2.3%); nitrate N (5.0 and 3.6 kg ha^{-1}); P (22.8 and 27.5 mg kg^{-1}); and K (323 and 333 mg kg^{-1}) for 2013 and 2014, respectively, were similar. The average rainfall distribution during the 2 yr of the experiment deviated slightly from 30-yr average (normal; Table 1). Total rainfall in April, May, and July was greater in 2013 than in 2014, and vice versa for June and August. In general, total rainfall during the summer months (June–August) in both years were slightly higher than normal. Mean temperature and total GDD (calculated with 5°C base temperature) in 2013 and 2014 compared well to normal year, except for August where they differed slightly (Table 1).

Plot Management

Three spring camelina cultivars (Blaine Creek, Pronghorn, and Shoshone) were used in the study. In 2013, the window for planting was short. This was because the soil was too wet throughout March and April to perform any field work. As such, the seeding dates 122, 129, and 136 DOY were spaced at 1 wk interval. In 2014, camelina was initially seeded on 101, 114, and 125 DOY. However, because of complete loss of the crops from frost damage (temperature below –4°C) at a critical emerging stage of growth for the second and third seeding, the plots were tilled and replanted. Therefore, the actual seeding dates in 2014 were 101, 153, and 160 DOY. The experiments were set as randomized complete block in a split-plot arrangement with four replications, and effects of year being noncumulative by planting at different areas situated 50 m apart. The main plot treatments were the seeding dates, and subplot treatments were the camelina cultivars.

The experiments were established on a previously fallowed land under a reduced tillage system. The land was prepared by one-time disking with a tandem disk (Allis-Chalmer Co., Milwaukee, WI), followed by one-time harrowing with an arena groomer (Parma Co., Parma, ID). Subplots

Table 1. Mean temperature, growing degree-days, and total monthly precipitation at Wyarno, Sheridan, WY, in 2013 and 2014.

Month	Mean temperature			Total growing degree-days‡			Total precipitation		
	2013	2014	Normal†	2013	2014	Normal	2013	2014	Normal†
	°C						mm		
April	–0.70	5.9	6.30	113	175	182	51.9	22.9	33.3
May	10.2	11.7	11.5	455	431	407	90.8	58.6	65.5
June	17.0	16.0	16.8	680	583	678	84.9	99.9	62.2
July	22.6	21.1	21.5	997	946	957	25.6	9.60	30.4
August	22.7	20.0	20.4	1012	862	906	3.2	14.5	16.7
Total							256	205	208

† Normal = 30-yr average.

‡ Growing degree-days were calculated using 5°C base temperature.

were approximately 1.5 by 6 m, and were seeded at a rate of 5.6 kg ha^{-1} to a depth of 7 mm using a cone drill seeder. Seed germination was tested before every seeding to adjust for the seeding rates. Urea was applied at a rate of 56 kg N ha^{-1} by broadcasting. Round-up [glyphosate; isopropylamine salt of N-(phosphonomethyl) glycine] was applied at 1.8 kg a.i. ha^{-1} to control weeds prior to seeding. Post-emergence weed control was performed manually by hand removing the weeds. Flea beetle (*Phyllotreta cruciferae*) infestation was observed during the 2014 cropping season but not in 2013. This observation could be due to canola (*Brassica napus* L.) that was cultivated near the experimental site in 2013, but not in 2014, suggesting that camelina is possibly an alternate host to flea beetle. Sevin SL (Carbaryl; 1-naphthol N-methylcarbamate) insecticide was applied at 1.5 kg a.i. ha^{-1} to control flea beetle on 3 June 2014. The flea beetle damage was rated visually on a 1 to 10 point scale for the first seeding date before applying the insecticide. The cultivars did not differ in flea beetle infestation, showing an average of 16% damage.

Data Collection

Before seeding, the 1000-seed weights (adjusted to 8% moisture content) of the camelina cultivars were measured. Plant establishment data were collected at the 2 to 3 leaf stage by counting the number of camelina seedlings within a 1-m row at 10 randomly selected locations within a plot. The data was used to calculate the average number of plants per meter square. The percentage of plant emergence was computed as the ratio of plants emerged to the total number of seeds planted multiplied by 100. Flowering date was recorded when 50% of the plants were at anthesis and the pod date when 50% of the pods were formed. Flowering period referred to the number of days between date of anthesis and pod date, and the days to maturity represented the number of days between seeding to when the plants were harvested. The GDD of plant emergence, flowering, and maturity were calculated as:

$$\mathrm{GDD}=\sum_{i}^{j}\frac{T_{\max}+T_{\min}}{2}-T_{\mathrm{base}} \qquad [1]$$

where T_{max} and T_{min} are daily maximum and minimum air temperature, respectively, and T_{base} was the base temperature. The GDD was calculated with 5°C base temperature (Aiken et al., 2015).

Average plant height was determined by measuring the length of 10 randomly selected plants from the soil surface to the highest point on the plant at the time of maturity. Plant stand at maturity was determined the same as to plant stand at emergence. Plants were harvested when 75% of the silicles were ripe (Sintim et al., 2015a). Entire plots were harvested with a hedge trimmer at the soil surface (taking care to avoid shattering) and the total aboveground biomass weighed before threshing with a portable stationary thresher, cleaned, and then weighed to determine seed weight. The crop harvest index was calculated as dry seed weight divided by dry weight of total aboveground biomass at harvest. Seed yields were adjusted to 8% moisture content.

Camelina Seed Protein and Oil Content Analysis and Biodiesel Estimation

Seed protein and oil concentration were determined using Fourier transform near-infrared spectroscopy and a specific calibration derived for a scanning monochromater (Perten DA-7200, Perten Instruments, Hägersten, Sweden) according to McVay and Khan (2011). The seeds were air-dried, and the moisture content measured before the oil analysis. Oil content in the seed was adjusted to 8% seed moisture. Biodiesel yield was estimated according to Sintim et al. (2015b). The estimation assumed 80% extraction efficiency (Kemp, 2006), 10% postharvest loss, and oil yield conversion of 1 kg ha^{-1} to 0.439 L volume biodiesel.

Statistical Analysis

Data analysis was performed separately for each year because the seeding dates were very different. The PROC MIXED procedure in SAS 9.4 (SAS Institute, 2013) was used for the analysis. Seeding date and cultivar were treated as fixed effects, and then block was considered as random effects. Mean separations were conducted at $P < 0.05$, using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure. Validity of equal variance, normality, and independence assumptions on the error terms were confirmed by assessing the residuals.

RESULTS AND DISCUSSION

Phenological Growth Parameters

Seeding date × cultivar interaction was not significant on all measured phenological growth parameters for both years. Early seeding prolonged the days to plant emergence, flowering, and maturity in both years. In addition, early seeding resulted in longer flowering period or pod formation. However, GDD for the growth stages were not significantly different among the seeding date treatments (Table 2). In the central Great Plains region of Nebraska, Pavlista et al. (2011) observed a reduction in days to plant emergence but later flowering date when camelina and canola were late seeded. Similar results have been reported previously (Zheng et al., 1994; Kirkland and Johnson, 2000). According to Nykiforuk and Johnson-Flanagan (1994), prolonged days to emergence with early seeding is a result of low soil temperature. Despite observing an effect of seeding date on emergence and flowering dates, Pavlista et al. (2011) reported no difference in the maturity date, contrary to what we observed.

Previous studies indicated camelina matures between 85 and 100 d after seeding, when grown in the northern Great Plains of Montana (McVay and Lamb, 2008). However, depending on year and seeding date, camelina matured earlier or later (75–112 d) in our current study (Table 2) than what was previously reported. The lack of difference in GDD in this study to seeding dates, even though calendar days varied significantly, emphasizes that accumulation of heat units is the important factor for determining growth stages of plants. As such, specifying number of days in which emergence, flowering, or maturity is expected to occur will not be relevant depending on prevailing weather conditions. Photoperiod has also been reported to influence days to flowering of camelina (Gesch and Cermak, 2011). In the present study, the average GDD for emergence, flowering, and maturity were 34, 417, and 998, respectively. The GDD for flowering was lower than what was

Table 2. The number of calendar days and growing degree-days required for emergence, flowering, and maturity of camelina as affected by seeding date in 2013 and 2014.

Seeding date	Emergence	Emergence	Flowering	Flowering	Flowering period	Maturity	Maturity
DOY†	DAP	GDD‡	DAP	GDD‡	days	DAP	GDD‡
2013							
122	7.1 ± 0.23a§	30.6 ± 1.66a	50 ± 0.37a	402 ± 4.69a	13.0 ± 0.21a	79 ± 1.16a	1005 ± 21.4a
129	3.3 ± 0.13b	31.9 ± 1.45a	43 ± 0.48b	392 ± 11.1a	12.1 ± 0.19b	79 ± 0.71a	997 ± 11.1a
136	3.2 ± 0.13b	32.5 ± 1.04a	42 ± 0.36b	402 ± 5.61a	12.6 ± 0.15ab	76 ± 0.43b	1000 ± 7.3a
P value	<0.001	0.734	<0.001	0.621	0.013	<0.001	0.244
2014							
101	13 ± 0.34a	37.5 ± 0.29a	72 ± 1.23a	406 ± 14.1a	13.3 ± 0.33a	112 ± 1.37a	970 ± 23.6a
153	2.5 ± 0.15b	35.2 ± 1.42a	41 ± 0.39b	441 ± 6.52a	11.3 ± 0.36b	84 ± 0.58b	1019 ± 8.51a
160	2.3 ± 0.13b	38.6 ± 1.31a	38 ± 0.43b	459 ± 7.56a	10.6 ± 0.28b	79 ± 0.43c	996 ± 4.75a
P value	<0.001	0.431	<0.001	0.101	0.003	<0.001	0.384

† DOY, day of year; DAP, days after planting; GDD, growing degree-days.

‡ GDD was calculated using 5°C base temperature.

§ Within column and year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ($P < 0.05$). Data are averaged across three camelina cultivars and four replications ($n = 12$), followed by the standard error of the mean.

reported by Gesch and Cermak (2011) for two winter camelina cultivars near Morris, MN. The authors observed 540 and 555 GDD (under no-till and chisel plowed, respectively) for camelina cultivar BSX-WG I and 577 and 584 GDD (under no-till and chisel plowed, respectively) for cultivar Joelle in the 2007–2008 cropping season. The lower GDD in the present study compared to that reported by Gesch and Cermak (2011) may be due to the different base temperature (5 vs. 4°C) and cultivar (spring vs. winter type).

Though early seeding prolonged the number of days to various growth stages, early seeded plots emerged, flowered, and matured at an earlier calendar date relative to delayed seeding. Flowering before the usual summer heat and drought period can help prevent pod abortion or other forms of stresses that cause premature senescence (Adamsen and Coffelt, 2005; Chen et al., 2005). According to Clayton et al. (2004), heat and moisture stress as a result of late seeding can hasten crop maturity. Hence, the shorter flowering time on late seeding might be due to a more rapid accumulation of GDD under warmer conditions that the late seeded plants may have experienced. Wang et al. (2003) indicated that plants respond to harsh temperatures through physiological adaptations.

The cultivars used in this study emerged at similar times, but Pronghorn flowered and matured earlier than Blaine Creek and Shoshone in both years (Table 3). Low profitability of wheat (*Triticum aestivum* L.)–fallow system in dry areas of the Great Plains has raised the need to replace the fallow phase with an alternative crop (DeVuyst and Halvorson, 2004; Obour et al., 2015). The crop must be well adapted to the region and possess unique qualities that will fit into the cropping system. Identifying short growing camelina cultivars such as Pronghorn in this study will be important for successful incorporation of camelina into dryland wheat-based production systems. This is because shorter growing cultivars will

Table 3. Cultivar effects on the number of calendar days and growing degree-days required for emergence, flowering, and maturity of camelina in 2013 and 2014.

Cultivar	Emergence	Emergence	Flowering	Flowering	Flowering period	Maturity	Maturity
	DAP†	GDD‡	DAP	GDD	days	DAP	GDD
2013							
Blaine C.	4.6 ± 0.60a§	31.7 ± 1.30a	45 ± 1.13a	399 ± 5.05ab	12.6 ± 0.19b	80 ± 0.57a	1025 ± 2.54a
Pronghorn	4.5 ± 0.56a	31.4 ± 1.28a	44 ± 1.16b	386 ± 10.2b	12.0 ± 0.17c	75 ± 0.28b	939 ± 7.37b
Shoshone	4.5 ± 0.56a	31.7 ± 1.29a	46 ± 1.14a	410 ± 5.14a	13.1 ± 0.15a	80 ± 0.75a	1037 ± 7.42a
P value	0.387	0.305	<0.001	0.022	<0.001	<0.001	<0.001
2014							
Blaine C.	5.7 ± 1.42a	37.1 ± 1.21a	50 ± 4.82a	441 ± 9.89a	12.1 ± 0.29a	93 ± 4.54a	1006 ± 17.1b
Pronghorn	5.8 ± 1.45a	37.1 ± 1.23a	48 ± 4.55b	413 ± 12.2b	10.7 ± 0.40b	90 ± 4.37b	971 ± 16.0c
Shoshone	5.8 ± 1.50a	37.6 ± 1.34a	51 ± 4.76a	452 ± 10.6a	12.6 ± 0.45a	93 ± 4.73a	1010 ± 11.5a
P value	0.195	0.348	<0.001	<0.001	<0.001	0.001	0.003

† DAP, days after planting; GDD, growing degree-days.

‡ GDD was calculated using 5°C base temperature.

§ Within column and year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ($P < 0.05$). Data are averaged across three seeding dates and four replications ($n = 12$), followed by the standard error of the mean.

mature early, allowing enough time for soil moisture recharge when adopted in wheat–fallow cropping systems. Differences in GDD for flowering and maturity among cultivars in the present study may be attributed to varying photoperiod sensitivity similar to that reported for winter camelina cultivars by Gesch and Cermak (2011).

Plant Emergence and Stand at Maturity

Plant emergence and stand at maturity was not affected by seeding date; however, they differed significantly among the cultivars (Table 4). Average plant emergence was 27 and 23%, respectively, for 2013 and 2014. Plant emergence (20–28%) was similar to what was reported in Nova Scotia and considerably lower (45–72%) compared to Prince Edward Island Provinces in Canada (Urbaniak et al., 2008). In contrast to our current study, seeding date was observed to affect camelina emergence at four sites in the Pacific Northwest (Lind, WA; Pendleton, OR; Moscow, ID; and Corvallis, OR) from 2008 to 2010, except for 2010 at Pendleton (Schillinger et al., 2012). Though the seeding dates analyzed in this study showed no difference in plant emergence, complete loss of initial second and third seeding in 2014 due to low temperatures in this study, suggests that seeding date can play a significant role in emergence of camelina.

Blaine Creek and Pronghorn had better emergence and stand at maturity than Shoshone. Plant stand at maturity was considerably lower than it was at emergence, implying some of the plants that emerged thinned-out during crop growth. On average, 43, 44, and 35% for Blaine Creek, Pronghorn, and Shoshone, respectively, in 2013 and 42, 43, and 29% for Blaine Creek, Pronghorn, and Shoshone, respectively, in 2014 of the plants that emerged thinned-out. Loss in plant stand from emergence to crop maturity was not unprecedented because of the small seed size and increased competition for water, nutrient sources, and light (Leach et al., 1999). Not surprising, Shoshone with the least plant emergence had fewer plants thinned-out.

Plant Height, Seed Yield, and Harvest Index

There was a significant interaction effect of seeding date and cultivar on plant height in 2014 but not in 2013 (Fig. 1). Early seeding resulted in taller plants among the cultivars. Blaine Creek was generally the tallest cultivar, except when planted on 153 DOY in 2014 where the cultivars had similar plant height. Average plant height ranged from 64 to 76 cm in 2013 and 59 to 77 cm in 2014. This was comparable to camelina plant height of 64 to 72 cm reported by Pavlista et al. (2011). There was no seeding date × cultivar interaction effect on seed yield and harvest index. Seeding date had no significant effect on the seed yield in 2013. However, seeding date affected camelina seed yield in the 2014 growing season. Delayed seeding in 2014 (153 and 160 DOY) resulted in decreased seed yield compared to when camelina was seeded early (101 DOY; Fig. 2). Our results are in agreement with the findings of previous studies (Berti et al., 2011; Schillinger et al., 2012) that showed that early seeding enhanced camelina performance and increased seed yields. However, under irrigated conditions in Scottsbluff, NE, Pavlista et al. (2011) reported no seed yield advantage in planting camelina early. This indicated that significant yield benefit of early seeding under rain-fed conditions may be attributable to soil moisture availability. In dryland agriculture, moisture availability plays a significant role in crop performance and seeding camelina late could result in moisture stress during reproductive stages of crop growth due to untimely rainfall distribution. Under dry conditions plants shed their leaves, which limits source (photosynthate) for seed yield (Gan et al., 2004). However, camelina was able to compensate for slight delays in seeding without significant effect on seed yield in this study. This was observed in 2013 when seeding dates were spaced at 1 wk intervals.

It is imperative to note that timely seeding, not necessarily early seeding is the important factor in camelina production. This is because frost at temperature of −4.4°C completely damaged young camelina seedlings at critical emerging stages when seeded on 114 and 125 DOY. Even the late seeded plots (166 DOY) produced seed yield of 509 kg ha^{-1}; whereas those seeded earlier (114 and 125 DOY) produced nothing. Camelina seedlings planted on 101 DOY were able to withstand the low temperatures because they were well established before onset of the frost.

Among the three cultivars studied, Blaine Creek and Pronghorn showed promise for higher seed production under rain-fed conditions in drier areas of the Great Plains such as Wyoming (Table 4). Yields were generally higher in 2013 than in 2014. The reason is because yields are averaged across seeding

Table 4. Plant emergence, plant stand at maturity, seed yield, and harvest index in 2013 and 2014 as affected by camelina cultivar.

Cultivar	Plant emergence	Plant stand at maturity	Seed yield	Harvest index
	%	%	kg ha^{-1}	
2013				
Blaine C.	35 ± 2.02a†	20 ± 0.98a	1018 ± 49.0a	0.243 ± 0.003a
Pronghorn	32 ± 1.64a	18 ± 0.58a	1068 ± 49.4a	0.246 ± 0.003a
Shoshone	14 ± 1.31b	8.7 ± 0.86b	932 ± 44.7b	0.246 ± 0.003a
P value	<0.001	<0.001	<0.001	0.137
2014				
Blaine C.	28 ± 2.32a	16 ± 1.44a	843 ± 117a	0.196 ± 0.025b
Pronghorn	26 ± 1.97a	15 ± 1.15a	858 ± 111a	0.239 ± 0.025a
Shoshone	14 ± 1.93b	9.8 ± 1.33b	720 ± 88.7b	0.210 ± 0.020b
P value	<0.001	<0.001	0.001	<0.001

† Within column and year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ($P < 0.05$). Data are averaged across three seeding dates and four replications ($n = 12$), followed by the standard error of the mean.

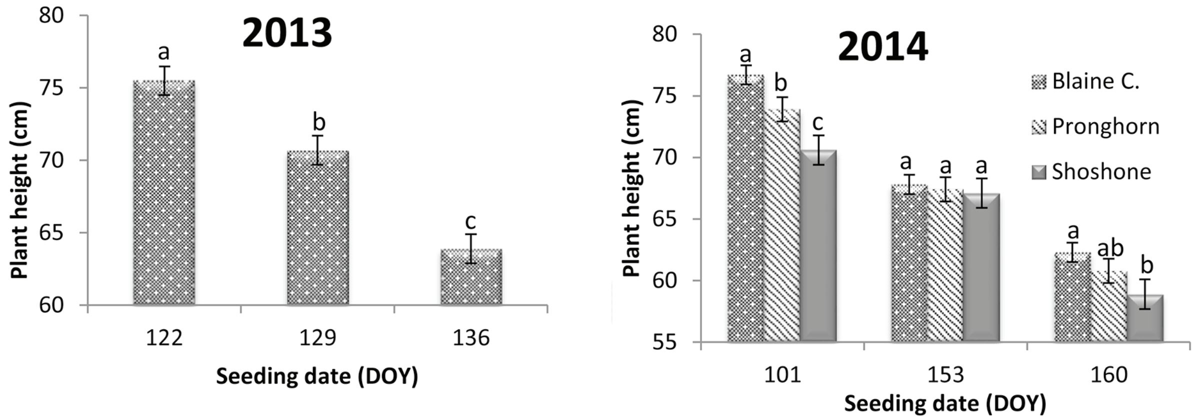

Fig. 1. Plant height as affected by seeding date. Data are averaged across three camelina cultivars and four replication (n = 12) in 2013; whereas in 2014, they were averaged across four replication (n = 4). Within year or cultivar, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure (P < 0.05). Error bars represent 1 SE of the mean.

dates and the two late seeding dates (153 and 160 DOY) in 2014 produced very low yields 698 and 509 kg ha^{-1}, respectively. However, seed yield when camelina was seeded early in 2014 (101 DOY) was greater (1214 kg ha^{-1}) than the highest yield for 2013 (1174 kg ha^{-1}). Reported camelina seed yield in Lingle, WY which is much drier than Sheridan, WY was 410 to 520 kg ha^{-1} (Aiken et al., 2015). In wetter climates, seed yield of 1338 to 1599 kg ha^{-1} has been reported in Canada (Urbaniak et al., 2008) and as high as 2314 kg ha^{-1} in Chile (Berti et al., 2011).

In 2013, seeding date had no effect on the crop harvest index, whereas in 2014 harvest index increased with early seeding, similar to seed yield (Fig. 2). In addition, harvest index of the cultivars in 2013 was similar but differed in 2014. Pronghorn (0.239) showed the highest crop harvest index compared to Blaine Creek (0.196) and Shoshone (0.210). In Chile, Berti et al. (2011) observed significant effect of seeding date on crop harvest index of camelina at only one location out of five locations studied. Camelina harvest index observed in our current study (0.159–0.320), compares well with that reported

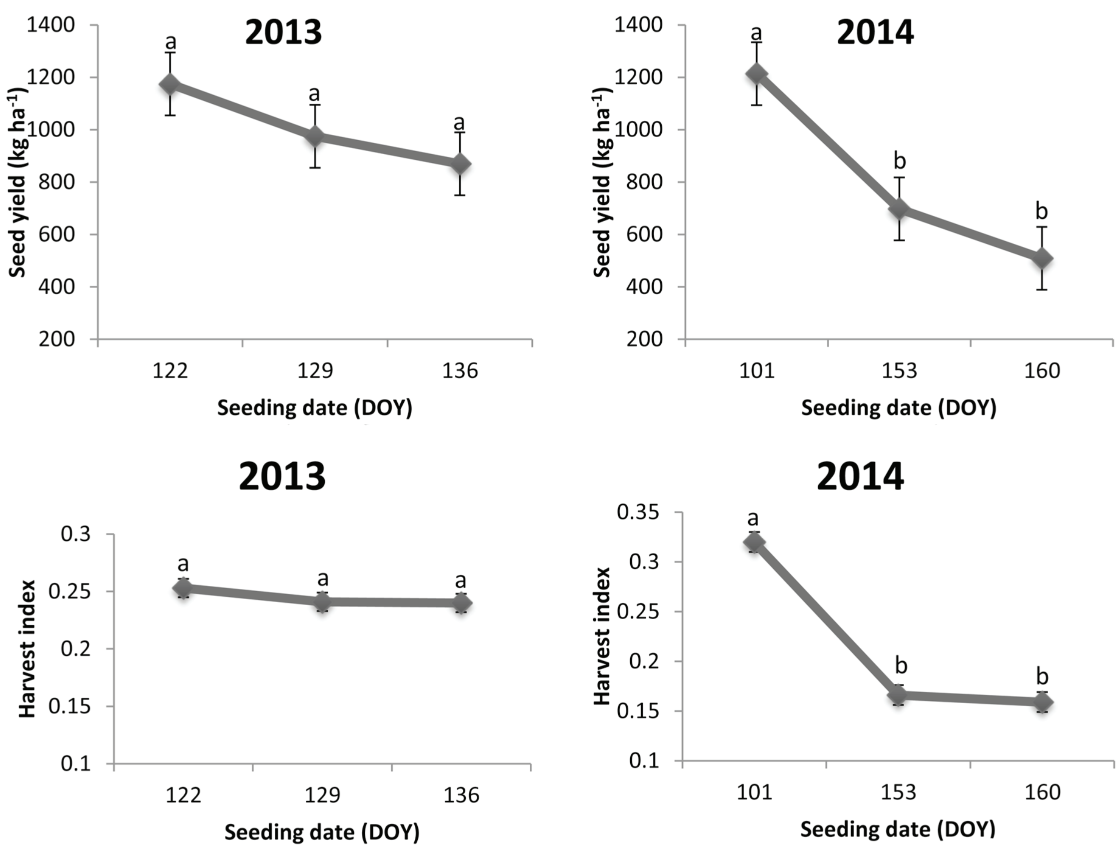

Fig. 2. Harvest index and seed yield as affected by seeding date. Data are averaged across three camelina cultivars and four replication (n = 12). Within year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure (P < 0.05). Error bars represent 1 SE of the mean.

in the literature (Gesch and Cermak, 2011; Solis et al., 2013; Liu et al., 2015).

The differential responses of camelina cultivars to year or seeding date shows that the cultivars had unique physiological and biochemical adaptations because of genetic variability, and/or their interactions with environmental factors. According to Fujita et al. (2014), genetic differences among camelina cultivars have a large influence on their uptake and efficient utilization of soil nutrients, and subsequent biomass and grain production. This was confirmed in our current study as the cultivars showed differences in plant height, seed yield, and harvest index.

Camelina Protein, Oil, and Biodiesel

There was a general reduction in protein content with early seeding in both years (Tables 5 and 6). However, protein yield was greatest in the first seeding dates in both years. Blaine Creek was the superior cultivar in terms of protein content in 2013; however, in 2014, the cultivars had similar protein content. In general, protein yield was greater in Blaine Creek and Pronghorn than in Shoshone. Contrary to seed protein, camelina oil content increased with early seeding. Subsequently, it translated to higher estimated biodiesel yield since seed yield increased somewhat when camelina was planted early. This was more evident in 2013 when seed yield was not affected by seeding date, but there were significant differences in estimated biodiesel yield. Blaine Creek had the least oil content in both years, but not the least estimated biodiesel yield because it yielded more seeds than Shoshone.

Pearson correlation analysis showed an inverse association between the seed protein and oil concentration of camelina (Fig. 3), which was consistent with previous studies (Jiang et al., 2013; Sintim et al., 2015b). According to Canvin (1965), temperature has profound effects on the oil content of rapeseed and flax, observing highest oil content in both rapeseed and flax at low temperatures and a continual decrease as temperature during crop growth increased. Reduction in seed oil content as a result of increased average daily temperature during seed development in *Cuphea* sp. has also been reported (Berti and Johnson, 2008). Saldivar et al. (2011) indicated that levels of protein in sunflower [*Helianthus annuus* (L.) Crantz] decreased by 20 to 60 g kg^{-1} during the first 3 to 5 wk after flowering and gradually increased thereafter until maturity. They attributed it to rapid synthesis of oil and starch during early seed development.

Table 5. Camelina protein content, protein yield, oil content, and estimated biodiesel yield as affected by seeding date in 2013 and 2014.

Seeding date	Protein content	Protein yield	Oil content	Calculated biodiesel yield
DOY†	g kg^{-1}	kg ha^{-1}	g kg^{-1}	L ha^{-1}
2013				
122	290 ± 2.98b‡	349 ± 14.6a	354 ± 3.46a	124 ± 4.93a
129	297 ± 2.16b	290 ± 6.71b	339 ± 2.46b	96.5 ± 2.27b
136	310 ± 2.13a	270 ± 8.50b	322 ± 4.48c	82.0 ± 2.84c
P value	0.002	0.007	<0.001	0.001
2014				
101	291 ± 3.64b	350 ± 22.5a	326 ± 4.78a	116 ± 9.99a
153	321 ± 2.79a	224 ± 11.3b	312 ± 3.85a	65.0 ± 3.74b
160	322 ± 2.06a	164 ± 7.80b	305 ± 6.11b	45.4 ± 2.56b
P value	0.004	0.004	0.041	0.009

† DOY, day of year.

‡ Within column and year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure (*P* < 0.05). Data are averaged across three camelina cultivars and four replications (*n* = 12), followed by the standard error of the mean.

Table 6. Cultivar effects on camelina protein content, protein yield, oil content, and estimated biodiesel yield in 2013 and 2014.

Cultivar	Protein content	Protein yield	Oil content	Calculated biodiesel yield
	g kg^{-1}	kg ha^{-1}	g kg^{-1}	L ha^{-1}
2013				
Blaine C.	304 ± 2.92a†	305 ± 14.3a	324 ± 5.29b	95.8 ± 6.05b
Pronghorn	297 ± 3.89b	320 ± 13.0a	344 ± 3.96a	109 ± 6.38a
Shoshone	298 ± 3.29b	277 ± 11.8b	344 ± 3.99a	94.2 ± 5.38b
P value	0.017	<0.001	<0.001	<0.001
2014				
Blaine C.	314 ± 5.79a	257 ± 30.0a	300 ± 4.87c	75.4 ± 11.6ab
Pronghorn	312 ± 5.82a	261 ± 27.5a	330 ± 3.58a	83.4 ± 11.7a
Shoshone	309 ± 3.63a	219 ± 24.1b	318 ± 4.37b	67.8 ± 9.02b
P value	0.066	<0.001	<0.001	0.001

† Within column and year, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure (*P* < 0.05). Data are averaged across three seeding dates and four replications (*n* = 12), followed by the standard error of the mean.

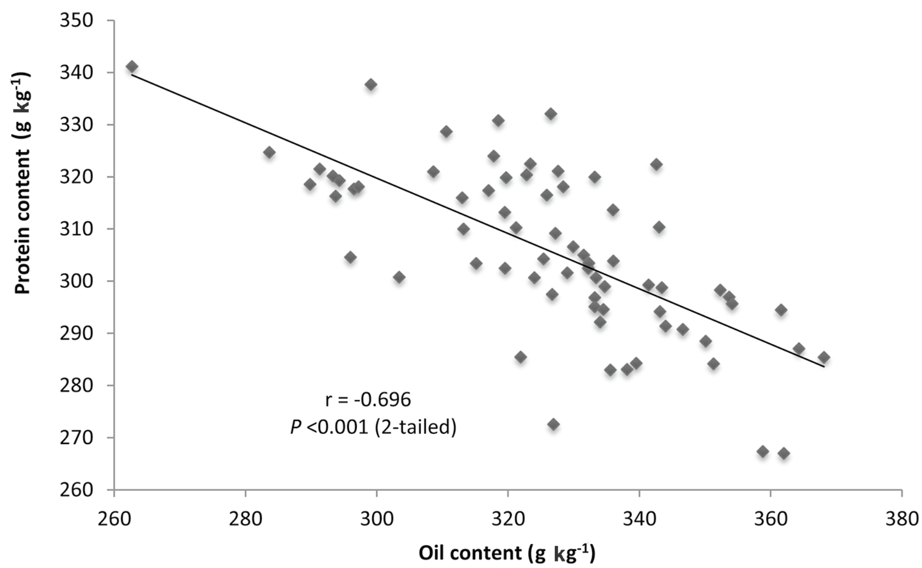

Fig. 3. Pearson correlation showing inverse relation between the seed protein and oil concentration of camelina.

CONCLUSIONS

The number of days from seeding to crop maturity was higher with early seeding. However, early seeded camelina matured at early dates compared to when it was late seeded. Early seeding also enhanced plant growth, seed yield, oil content, and estimated biodiesel yields. Nonetheless, early seeding was restrained by wet field conditions in 2013. Camelina is commonly identified as a cold tolerant crop, but in this study, cold temperatures in the spring of 2014 (temperatures below −4°C) caused complete loss to camelina seedlings soon after plants had emerged. Camelina seedlings withstood the frost when they were well established. Flea beetle damage of camelina as a result of the absence of their main host was also observed and could be a potential challenge to camelina production.

Among the three cultivars studied, Blaine Creek and Pronghorn had better establishment and subsequent seed yield in both years. Pronghorn was the earliest maturing cultivar and this can provide enough time for soil water recharge when incorporated in the fallow phase in cropping systems with wheat. The results indicate that seeding camelina as early as field conditions permit in northern Wyoming, while avoiding the potential for hard frosts, enhances its growth, seed yield, and oil content. In general, camelina shows promise as a potential oilseed crop that can be cultivated under rain-fed conditions in water-limited environments.

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REFERENCES

Adamsen, F.J., and T.A. Coffelt. 2005. Seeding date effects on flowering, seed yield, and oil content of rape and crambe cultivars. Ind. Crops Prod. 21:293–307. doi:10.1016/j.indcrop.2004.04.012

Aiken, R., D. Baltensperger, J. Krall, A. Pavlista, and J. Johnson. 2015. Planting methods affect emergence, flowering and yield of spring oilseed crops in the U.S. Central High Plains. Ind. Crops Prod. 69:273–277. doi:10.1016/j.indcrop.2015.02.025

Allen, B.L., M.F. Vigil, and J.D. Jabro. 2014. Camelina growing degree hour and base temperature requirements. Agron. J. 106:940–944. doi:10.2134/agronj13.0469

Baligar, V.C., N.K. Fageria, and Z.L. He. 2001. Nutrient use efficiency in plants. Commun. Soil Sci. Plant Anal. 32:921–950. doi:10.1081/CSS-100104098

Bernardo, A., R. Howard-Hildige, A. O'Connell, R. Nichol, J. Ryan, B. Rice et al. 2003. Camelina oil as a fuel for diesel transport engines. Ind. Crops Prod. 17:191–197. doi:10.1016/S0926-6690(02)00098-5

Berti, M.T., and B.L. Johnson. 2008. Physiological changes during seed development of cuphea. Field Crops Res. 106:163–170. doi:10.1016/j.fcr.2007.11.007

Berti, M., R. Wilckens, S. Fischer, A. Solis, and B. Johnson. 2011. Seeding date influence on camelina seed yield, yield components, and oil content in Chile. Ind. Crops Prod. 34:1358–1365. doi:10.1016/j.indcrop.2010.12.008

Budin, J.T., W.M. Breene, and D.H. Putnam. 1995. Some compositional properties of camelina (*Camelina sativa* L. Crantz) seeds and oils. J. Am. Oil Chem. Soc. 72:309–315. doi:10.1007/BF02541088

Canvin, D.T. 1965. The effect of temperature on the oil content and fatty acid composition of the oils from several oil seed crops. Can. J. Bot. 43:63–69. doi:10.1139/b65-008

Chen, C., G. Jackson, K. Neill, D. Wichman, G. Johnson, and D. Johnson. 2005. Determining the feasibility of early seeding canola in the Northern Great Plains. Agron. J. 97:1252–1262. doi:10.2134/agronj2005.0004

Clayton, G.W., K.N. Harker, J.T. O'Donovan, R.E. Blackshaw, L.M. Dosdall, F.C. Stevenson, and T. Ferguson. 2004. Fall and spring seeding date effects on herbicide-tolerant canola (*Brassica napus* L.) cultivars. Can. J. Plant Sci. 84:419–430. doi:10.4141/P03-149

DeVuyst, E.A., and A.D. Halvorson. 2004. Economics of annual cropping versus crop–fallow in the Northern Great Plains as influenced by tillage and nitrogen. Agron. J. 96:148–153. doi:10.2134/agronj2004.0148

Fujita, K., S. Fujita, T. Fujita, S. Konishi, J. Vollmann, P.K. Mohapatra et al. 2014. Source-sink manipulation of *Camelina sativa* L. related to grain yield under stressful environment of Hokkaido, Japan. Soil Sci. Plant Nutr. 60:156–161. doi:10.1080/00380768.2013.879259

Gan, Y., S.V. Angadi, H. Cutforth, D. Potts, V.V. Angadi, and C.L. McDonald. 2004. Canola and mustard response to short periods of temperature and water stress at different developmental stages. Can. J. Plant Sci. 84:697–704. doi:10.4141/P03-109

Gesch, R.W., and S.C. Cermak. 2011. Sowing date and tillage effects on fall-seeded camelina in the Northern Corn Belt. Agron. J. 103:980–987. doi:10.2134/agronj2010.0485

Gugel, R.K., and K.C. Falk. 2006. Agronomic and seed quality evaluation of *Camelina sativa* in western Canada. Can. J. Plant Sci. 86:1047–1058. doi:10.4141/P04-081

Jiang, Y., C.D. Caldwell, K.C. Falk, R.R. Lada, and D. MacDonald. 2013. Camelina yield and quality response to combined nitrogen and sulfur. Agron. J. 105:1847–1852. doi:10.2134/agronj2013.0240

Kemp, W.H. 2006. Biodiesel: Basics and beyond, a comprehensive guide to production and use for the home and farm. Aztext Press. Tamworth, Ontario, Canada.

Kirkland, K.J., and E.N. Johnson. 2000. Alternative seeding dates (fall and April) affect *Brassica napus* canola yield and quality. Can. J. Plant Sci. 80:713–719. doi:10.4141/P00-016

Leach, J.E., H.J. Stevenson, A.J. Rainbow, and L.A. Mullen. 1999. Effects of high plant populations on the growth and yield of winter oilseed rape (*Brassica napus*). J. Agric. Sci. 132:173–180. doi:10.1017/S0021859698006091

Liu, J., H. Tjellström, K. McGlew, V. Shaw, A. Rice, J. Simpson et al. 2015. Field production, purification and analysis of high-oleic acetyl-triacylglycerols from transgenic *Camelina sativa*. Ind. Crops Prod. 65:259–268. doi:10.1016/j.indcrop.2014.11.019

Matthäus, B., and J. Zubr. 2000. Variability of specific components in *Camelina sativa* oilseed cakes. Ind. Crops Prod. 12:9–18. doi:10.1016/S0926-6690(99)00040-0

McVay, K.A., and Q.A. Khan. 2011. Camelina yield response to different plant populations under dryland conditions. Agron. J. 103:1265–1269. doi:10.2134/agronj2011.0057

McVay, K.A., and P.F. Lamb. 2008. Camelina production in Montana. Montana State Univ. Ext. Publ. 200701AG. Revised 8 March. Montana State Univ., Bozeman.

Moser, B.R., and S.F. Vaughn. 2010. Evaluation of alkyl esters from *Camelina sativa* oil as biodiesel and as blend components in ultra-low sulfur diesel fuel. Bioresour. Technol. 101:646–653. doi:10.1016/j.biortech.2009.08.054

Nykiforuk, C.L., and A.M. Johnson-Flanagan. 1994. Germination and early seedling development under low temperature in canola. Crop Sci. 34:1047–1054. doi:10.2135/cropsci1994.0011183X003400040039x

Obour, A.K., H.Y. Sintim, E. Obeng, and D.V. Zheljazkov. 2015. Oilseed camelina (*Camelina sativa* L Crantz): Production systems, prospects and challenges in the USA Great Plains. Adv. Plants Agric. Res. 2:1–10 10.15406/apar.2015.02.00043.

Pavlista, A.D., T.A. Isbell, D.D. Baltensperger, and G.W. Hergert. 2011. Planting date and development of spring-seeded irrigated canola, brown mustard and camelina. Ind. Crop Prod. 33:451–456. doi:10.1016/j.indcrop.2010.10.029

Pinzi, S., I.L. Garcia, F.J. Lopez-Gimenez, M.D. Luque de Castro, G. Dorado, and M.P. Dorado. 2009. The ideal vegetable oil-based biodiesel composition: A review of social, economical and technical implications. Energy Fuels 23:2325–2341. doi:10.1021/ef801098a

Saldivar, X., Y.J. Wang, P. Chen, and A. Hou. 2011. Changes in chemical composition during soybean seed development. Food Chem. 124:1369–1375. doi:10.1016/j.foodchem.2010.07.091

SAS Institute. 2013. SAS/STAT 9.4 user's guide. SAS Inst., Cary, NC.

Schillinger, W.F., D.J. Wysocki, T.G. Chastain, S.O. Guy, and R.S. Karow. 2012. Camelina: Planting date and method effects on stand establishment and seed yield. Field Crop Res. 130:138–144. doi:10.1016/j.fcr.2012.02.019

Shonnard, D.R., L. Williams, and T.N. Kalnes. 2010. Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environ. Prog. Sustain. Energy 29:382–392. doi:10.1002/ep.10461

Sintim, H.Y., V.D. Zheljazkov, and A. Obour. 2015a. Camelina (*Camelina sativa* Crantz) response to different harvest stages. PNW Oilseed and Direct Seed Conference, Kennewick, WA. 20–22 Jan. 2015. Washington State Univ., Pullman. http://css.wsu.edu/biofuels/files/2015/02/Poster24Jeliazkov.pdf (accessed 31 Oct. 2015).

Sintim, H.Y., V.D. Zheljazkov, A. Obour, A. Garcia y Garcia, and T.K. Foulke. 2015b. Influence of nitrogen and sulfur application on camelina performance under dryland conditions. Ind. Crop Prod. 70:253–259. doi:10.1016/j.indcrop.2015.03.062

Solis, A., I. Vidal, L. Paulino, B.L. Johnson, and M.T. Berti. 2013. Camelina seed yield response to nitrogen, sulfur, and phosphorus fertilizer in South Central Chile. Ind. Crops Prod. 44:132–138. doi:10.1016/j.indcrop.2012.11.005

Urbaniak, S.D., C.D. Caldwell, V.D. Zheljazkov, R. Lada, and L. Luan. 2008. The effect of seeding rate, seeding date and seeder type on the performance of *Camelina sativa* L. in the Maritime Provinces of Canada. Can. J. Plant Sci. 88:501–508. doi:10.4141/CJPS07148

Wang, W., B. Vinocur, and A. Altman. 2003. Plant responses to drought, salinity and extreme temperatures: Towards genetic engineering for stress tolerance. Planta 218:1–14. doi:10.1007/s00425-003-1105-5

Zaleckas, E., V. Makarevičienė, and E. Sendžikienė. 2012. Possibilities of using *Camelina sativa* oil for producing biodiesel fuel. Transport 27:60–66. doi:10.3846/16484142.2012.664827

Zheng, G.H., R.W. Wilen, A.E. Slinkard, and L.V. Gusta. 1994. Enhancement of canola seed germination and seedling emergence at low temperature by priming. Crop Sci. 34:1589–1593. doi:10.2135/cropsci1994.0011183X003400060031x

Zubr, J. 2003. Qualitative variation of *Camelina sativa* seed from different locations. Ind. Crops Prod. 17:161–169. doi:10.1016/S0926-6690(02)00091-2