Camelina (Camelina sativa L. Crantz) is an oilseed crop with the potential for dryland crop production in the Great Plains. However, pod shattering may cause significant yield losses. We determined the impact of different harvest times on camelina seed yield (SY), water use efficiency, protein and oil content, and estimated biodiesel yield. Spring (Blaine Creek) and winter (BX WG1) camelina cultivars were harvested at three different stages, corresponding to the three-digit Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) scales of 805 (early harvest; 50% ripe pods), 807 to 808 (mid-harvest; 70–80% ripe pods), and 809 (late harvest; >90% ripe pods). In addition, different harvest methods were assessed to identify and quantify other sources of yield loss. Seed moisture contents at early, mid, and late harvests were 14.2, 9.8, and 6.8%, respectively. On average, the SY of early harvest was 95 and 23.6% greater than the mid- and late harvests, respectively. Total seed loss incurred during direct-combine harvest was 11.7%, which was attributable to the mechanical disturbance imposed on the pods and the combine settings. Camelina seed oil content was greatest at mid-harvest, but the estimated biodiesel yield was not significantly different between the early and mid-harvests. In general, direct combining when 75% of camelina pods are ripe will provide a balance between SY loss and the seed protein and oil contents.
Despite camelina’s agronomic potential, uneven maturity and other production factors such as shattering that result in significant yield losses have constrained its production (McVay and Khan, 2011; Obour et al., 2015). Sintim et al. (2014) reported a 28.9% higher SY loss when camelina was direct combined compared to plants that were carefully harvested with pruners and then threshed with a portable stationary thresher. This result suggests that mechanical disturbance during combine harvesting (causing pod shattering), the type of combine, and the combine settings such as the fan speed, concave adjustment, and sieve size can result in significant seed loss. Excessive combine travel speed could lead to significant yield losses because camelina seeds are very small. Large sieve opening size may reduce yield losses, but will retain more residues in the harvested seeds. Rainfall after crop maturity caused significant shattering and complete SY loss in a camelina trial in Laramie, WY (unpublished data, 2015). In addition, windy weather conditions, prevalent in Wyoming and other regions in the Great Plains can result in significant SY loss from pod shattering before harvest.

Swathing is usually recommended for crops that are prone to shattering. The process includes pre-harvesting a crop with a windrower/swather before pod ripening, and allowing them to air dry before threshing. Although this practice is important to reduce SY loss from shattering, it can affect seed quality due to a greater seed chlorophyll content (Vera et al., 2007). Additionally, swathing is labor intensive and increases the total production cost (Gan et al., 2008; Vera et al., 2007). Management practices that select the optimal harvest time and method are necessary to reduce pod shattering. In this study, we (a) determined SY, water use efficiency, protein and oil contents, and estimated biodiesel yield of camelina harvested at different stages of pod ripening; and (b) assessed different harvest methods to identify and quantify various sources of yield loss.

MATERIALS AND METHODS

Experimental Management

The study was conducted at the University of Wyoming’s Research and Extension Center, at the Wyarno field site near 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 Haplorgid) and was characterized as very deep, well drained, <0.5% slope, and clay loam (33% sand, 36% silt, and 31% clay). Nutrient analysis of the soil showed at 15-cm depth was 5.38 kg ha⁻¹, 13.8 mg kg⁻¹, and 268 mg kg⁻¹ for nitrate N, available P, and exchangeable K, respectively. The pH and organic matter of the soil were 7.2 and 2.2%, respectively.

The current study was nested on a cropping systems trial that was established in the 2012–2013 growing season. The cropping systems study consisted of three crop rotations (winter wheat–fallow, winter wheat–winter camelina, and winter wheat–spring camelina) in a randomized complete block design (RCBD) with five replications. Camelina cultivars Blaine Creek (spring camelina) and BX WG1 (winter camelina) were used in this study. Individual plot sizes were approximately 12 by 52 m. Each phase of the cropping system was present in each block for each year of the study (total of six treatments), except in 2012 when winter camelina was not planted due to limited seed availability. Thus, this study analyzed 2-yr experimental data (2013 and 2014) for the spring camelina cultivar and only 1-yr data (2013–2014 growing season) for the winter cultivar. Camelina was seeded at a rate of 5.6 kg seed ha⁻¹ to a depth of 6.4 mm using a disk drill (John Deere model 9300, John Deere, Moline, IL). The spring cultivar was seeded on 13 May and 11 April in 2013 and 2014, respectively. The winter cultivar was seeded on 18 Oct. 2013. In the 2012–2013 growing season, camelina was planted on previously fallowed land maintained under a reduced tillage system, but it followed a wheat crop in the 2013–2014 growing season. Round-up [glyphosate; isopropylamine salt of N-(phosphonomethyl) glycine] was applied at 1.8 kg a.i. ha⁻¹ before seeding to provide burn-down of already emerged weed. Post-emergence grass weed control was performed by applying Fusilade [fluazifop-P-buty], at 1.1 kg a.i. ha⁻¹ in 2014. Weed pressure in 2013 was relatively low so no post-emergence weed control was performed. Both wheat and camelina plots received N fertilization as broadcast urea applied at 45 kg N ha⁻¹.

Treatments for this nested study included camelina harvested at three stages, corresponding to the three-digit BBCH scales of 805 (early harvest), 807 to 808 (mid-harvest), and 809 (late harvest). The harvest stages description was obtained from a BBCH scale developed for camelina (Martinelli and Galasso, 2011). Before every harvest, small plant samples were randomly collected from the plots and threshed to determine the seed moisture content. The seed moisture content was determined by the gravimetric method on wet basis by recording the seed weight before and after drying in an oven at 60°C for 48 h. At each harvest, two 1 by 1 m areas from the plots of spring and winter camelina cultivars were carefully harvested with pruners at the soil surface to avoid shattering. In addition, 1.6 by 52 m strips were direct-combine harvested with a regular plot combine (Almaco model PMC20, Almaco, Nevada, IA) at the time of the late harvest. The combine was first set to the recommended specification for canola harvest, and then the airflow was further adjusted to minimize seeds that were blown out, while reducing the amount of crop residue retained. Another harvest method included harvesting two 2 by 6 m strips with pruners at the time of the late harvest, and then threshing the harvested plants with the regular plot combine using the same combine fan speed when direct harvesting. Due to a mechanical problem, we were unable to direct combine in the 2014 harvest year.

Samples harvested from the 1 by 1 m² areas were air dried, weighed to determine the total aboveground biomass, and then the airflow was reduced to portable stationary thresher (Almaco model SVPT, Almaco, Nevada, IA) to avoid seed loss. Seeds were then cleaned and weighed to determine seed weight and the data used to estimate the crop harvest index. Seed yields were adjusted to 8% moisture content.

Camelina Seed Protein, 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 percent of oil content in the seed was adjusted to 8% seed moisture content. Biodiesel yield was estimated according to Sintim et al. (2015). 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.

**Soil Moisture and Water Use Determination**

A neutron probe (Campbell Pacific Nuclear, Inc., Concord, CA) calibrated for specific conditions of the experimental site was used to record soil moisture content in 20-cm depth increments to 80-cm total depth at seeding and after harvest. The water use (WU) in millimeters that occurred throughout the growing period was calculated as:

\[
WU = S_in - S_fi + P
\]

where \(S_in\) and \(S_fi\) are the soil water storages in millimeters within 80-cm soil depth at seeding and after harvest, respectively; and P is total precipitation (mm) between seeding and after harvest. Water use efficiency (WUE, kg m⁻³) for camelina was calculated as:

\[
WUE = SY/WU
\]

where SY is seed yield (kg ha⁻¹). Precipitation data was obtained from the research center’s weather station situated about 50 m away from the experimental site.

**Statistical Analysis**

Data analyses were performed utilizing the SAS 9.4 statistical package (SAS Institute, 2013). The validity of independence assumptions, equal variance, and normality on the error terms were confirmed by assessing the residuals (Montgomery, 2013). The first experiment (designated as Exp. 1) was a RCBD analysis for the spring cultivar in 2013 using the PROC GLM procedure. The second experiment (designated as Exp. 2) was a split-plot analysis for both the spring and winter camelina plots harvested in 2014 using the PROC MIXED procedure. Cultivar and harvest time were considered fixed effects, and block as random effect. Mean separations were conducted at \(P < 0.05\), using the least squares means (LSMEANS) and the adjusted Tukey multiple comparison procedure.

A third analysis, designated as Exp. 3, entailed a paired sample \(t\) test for the 1 by 1 m strips harvested with pruners at the late-harvest stage and either (a) the direct combine or (b) the 2 by 6 m strips harvested with pruners but threshed with the regular plot combine. The PROC TTEST procedure was used to perform the analysis.

**RESULTS**

**Weather Conditions**

The mean air temperature in 2013 and 2014 was similar and compared well with the 30-yr average (Table 1). However, total precipitation varied between the 2 yr and the 30-yr average (Table 1). Most of the precipitation occurred in May and June, with the exception of 2013 when precipitation was also high in September and October. The annual total precipitation in 2013 and 2014 was above the 30-yr average.

<table>
<thead>
<tr>
<th>Month</th>
<th>Total precipitation 2013</th>
<th>Total precipitation 2014</th>
<th>Total precipitation 30-yr average</th>
<th>Mean temperature 2013</th>
<th>Mean temperature 2014</th>
<th>Mean temperature 30-yr average</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>22.5</td>
<td>14.5</td>
<td>14.2</td>
<td>-6.27</td>
<td>-2.71</td>
<td>-4.55</td>
</tr>
<tr>
<td>February</td>
<td>21.4</td>
<td>14.1</td>
<td>13.7</td>
<td>-6.42</td>
<td>-8.69</td>
<td>-3.00</td>
</tr>
<tr>
<td>March</td>
<td>16.3</td>
<td>25.7</td>
<td>24.6</td>
<td>-0.415</td>
<td>0.660</td>
<td>1.75</td>
</tr>
<tr>
<td>April</td>
<td>51.9</td>
<td>22.6</td>
<td>40.6</td>
<td>-0.700</td>
<td>5.86</td>
<td>6.30</td>
</tr>
<tr>
<td>May</td>
<td>90.8</td>
<td>58.6</td>
<td>59.7</td>
<td>10.2</td>
<td>11.7</td>
<td>11.5</td>
</tr>
<tr>
<td>June</td>
<td>84.9</td>
<td>99.9</td>
<td>93.8</td>
<td>17.0</td>
<td>16.0</td>
<td>16.8</td>
</tr>
<tr>
<td>July</td>
<td>25.6</td>
<td>9.60</td>
<td>29.7</td>
<td>22.6</td>
<td>21.1</td>
<td>21.5</td>
</tr>
<tr>
<td>August</td>
<td>3.20</td>
<td>14.5</td>
<td>18.0</td>
<td>22.7</td>
<td>20.0</td>
<td>20.4</td>
</tr>
<tr>
<td>September</td>
<td>8.60</td>
<td>60.7</td>
<td>36.3</td>
<td>17.2</td>
<td>14.7</td>
<td>14.4</td>
</tr>
<tr>
<td>October</td>
<td>86.3</td>
<td>5.00</td>
<td>34.8</td>
<td>5.31</td>
<td>9.67</td>
<td>7.50</td>
</tr>
<tr>
<td>November</td>
<td>3.80</td>
<td>36.0</td>
<td>17.8</td>
<td>0.955</td>
<td>-2.00</td>
<td>0.350</td>
</tr>
<tr>
<td>December</td>
<td>20.9</td>
<td>24.0</td>
<td>14.2</td>
<td>-8.73</td>
<td>-4.30</td>
<td>-5.05</td>
</tr>
<tr>
<td>Total</td>
<td>436</td>
<td>385</td>
<td>357</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Experiment 1. Spring Camelina Response to Harvest Time in 2013**

Late harvest of spring camelina significantly reduced SY and harvest indices (Table 2). Compared to the early harvest, there were 11.5 and 26.0% reductions in SY for mid- and late harvests, respectively. Seed moisture at harvest was greatest when harvested early but decreased with delayed harvesting (14.5, 9.9, and 6.9% for early, mid, and late harvests, respectively). The recommended moisture content for storing camelina seeds is 8% (Hunter and Roth, 2014; Sintim, 2014). There were no significant effects of harvest time on the seed protein content, but the oil content was greatest at mid-harvest. In general, delaying camelina harvest resulted in reduced protein yield and estimated biodiesel yield (Table 2).

**Experiment 2. Camelina Response to Cultivar and Harvest Time**

On average, the SYs of early harvest were 7.23 and 20.9% greater than mid- and late harvests, respectively. The harvest index and seed moisture content were lowest at late harvest.
Table 2. Harvest time effects on seed yield, harvest index, seed moisture content, protein content, protein yield, oil content, and estimated biodiesel yield of spring camelina.

<table>
<thead>
<tr>
<th>Harvest times</th>
<th>Seed yield (kg ha⁻¹)</th>
<th>Harvest index</th>
<th>Seed moisture content (%)</th>
<th>Protein content (%)</th>
<th>Protein yield (kg ha⁻¹)</th>
<th>Oil content (%)</th>
<th>Estimated biodiesel yield (L ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>1195 ± 87.0a†</td>
<td>0.311 ± 0.013a</td>
<td>14.5 ± 0.468a</td>
<td>29.8 ± 0.339a</td>
<td>356 ± 27.7a</td>
<td>29.2 ± 0.161b</td>
<td>153 ± 11.2a</td>
</tr>
<tr>
<td>Mid</td>
<td>1057 ± 77.4b</td>
<td>0.307 ± 0.011a</td>
<td>9.88 ± 0.287b</td>
<td>30.4 ± 0.360a</td>
<td>321 ± 23.5b</td>
<td>31.2 ± 0.363a</td>
<td>145 ± 11.3a</td>
</tr>
<tr>
<td>Late</td>
<td>884 ± 65.0c</td>
<td>0.259 ± 0.011b</td>
<td>6.87 ± 0.285c</td>
<td>30.3 ± 0.491a</td>
<td>267 ± 20.2c</td>
<td>30.4 ± 0.557ab</td>
<td>118 ± 9.47b</td>
</tr>
</tbody>
</table>

† Within columns, means followed by the same letter(s) are not significantly different using the least squares means (LSMEANS) and the adjusted Tukey multiple comparison procedure (P < 0.05).

Table 3. Cultivar and harvest time effects on seed yield, harvest index, seed moisture content, water use, protein yield, oil content, and estimated biodiesel yield of spring and winter camelina cultivars.

<table>
<thead>
<tr>
<th>Harvest times</th>
<th>Seed yield (kg ha⁻¹)</th>
<th>Harvest index</th>
<th>Seed moisture content (%)</th>
<th>Water use (mm)</th>
<th>Protein yield (kg ha⁻¹)</th>
<th>Oil content (%)</th>
<th>Estimated biodiesel yield (L ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>1051 ± 45.4a†</td>
<td>0.264 ± 0.004a</td>
<td>14.2 ± 0.335a</td>
<td>296 ± 38.3a</td>
<td>239 ± 9.85a</td>
<td>33.6 ± 0.235b</td>
<td>155 ± 7.10a</td>
</tr>
<tr>
<td>Mid</td>
<td>975 ± 41.9b</td>
<td>0.266 ± 0.007a</td>
<td>9.81 ± 0.243b</td>
<td>301 ± 37.7a</td>
<td>221 ± 9.45b</td>
<td>34.7 ± 0.188a</td>
<td>148 ± 6.30a</td>
</tr>
<tr>
<td>Late</td>
<td>831 ± 34.4c</td>
<td>0.243 ± 0.006b</td>
<td>6.69 ± 0.263c</td>
<td>302 ± 36.0a</td>
<td>196 ± 8.23c</td>
<td>33.3 ± 0.264b</td>
<td>121 ± 5.07b</td>
</tr>
</tbody>
</table>

† Within harvest times, means followed by the same letters are not different using the least squares means (LSMEANS) and the adjusted Tukey multiple comparison procedure (P < 0.05).

(Table 3). Both winter and spring cultivars showed similar SYs, harvest indices, and seed moisture contents at harvest. However, water use in the spring cultivar (217 mm) was lower than that of the winter cultivar (382 mm). This effect may be due to the longer growth period (80–108 d vs. 266–294 d) of the winter cultivar. Water use efficiency was significantly influenced by cultivar × harvest time interaction (P = 0.0077). Late harvest resulted in a lower WUE for the spring cultivar; however, harvest time had no effect on the WUE for the winter cultivar. Overall, the spring cultivar had a greater WUE because it utilized less precipitation than the winter cultivar (Fig. 1).

The two cultivars showed similar protein yields, oil contents, and estimated biodiesel yield. Delaying harvest reduced the protein and estimated biodiesel yields. Cultivar and harvest time showed significant interaction effects on the seed protein content (P = 0.0499): There were no effects of harvest time on protein content for the spring cultivar, but protein content was greatest at late harvest for the winter cultivar. Although the test statistics was significant, the sums of squared of the interaction term was 2.54 compared to the total sums of squared of 21.9 and thus the interaction effect could be very marginal. Camelina seed oil contents at mid-harvest were 3.3 and 4.2% greater than the early and late harvests, respectively.

**Experiment 3. Camelina Response to Harvest Methods**

The harvest methods had significant effect on camelina SY. When camelina was harvested with pruners followed by threshing in a portable stationary thrasher, the SY was 853 and 808 kg ha⁻¹ for the spring and winter cultivars, respectively. However, SY was lower when camelina was harvested with pruners followed by threshing in a regular plot combine. Seed yields were 815 and 774 kg ha⁻¹ for the spring and winter cultivars, respectively. The SY differences between the two harvests corresponded to 4.5% for the spring cultivar and 4.2% for the winter cultivar. Direct-combining of the spring camelina in 2013 resulted in 11.7% reduction in SY compared to harvesting with pruners and threshing with portable stationary thrasher (781 vs. 884 kg ha⁻¹).
DISCUSSIONS

The results of this work support previous studies that indicated pod shattering is a potential constraint for camelina production systems (McVay and Khan, 2011; Obour et al., 2015; Sintim et al., 2014). Besides pod shattering, uneven maturity leads to harvest problems and SY losses (McVay and Khan, 2011). Uneven plant maturity could be attributed to differential seedling emergence. Lenssen et al. (2012) observed uneven emergence in camelina, with plants continuing to emerge 2 mo after planting. Furthermore, pods within the same branch of a plant could mature at different times. These observations suggest that both environmental and physiological factors cause uneven maturation in camelina, leading to harvest problems and subsequent yield losses. The SY loss is the result of immature pods that do not thresh when harvested occurred early. When harvesting is delayed, the pods that matured early most likely will shatter before harvest time. In the current study, we observed up to 23.6% average SY losses when camelina was harvested late compared to early harvest, which we attributed to pod shattering. Bruce et al. (2002) indicated that at full pod ripening, it only takes minimal force to cause pod shattering in oilseed rape, due to the presence of a dehiscence zone of thinned and partially separated cells that conduct a fracture. According to Vera et al. (2007), an occurrence of strong wind can also lead to large seed losses if harvest is delayed. Wyoming is characterized by strong wind conditions, suggesting a reason for significant SY loss due to pod shattering when harvesting is delayed.

Seed yield losses after harvesting with pruners and threshing spring camelina with a plot combine was 7.3% lower than the direct combining method. This result suggests greater SY loss from the mechanical disturbance imposed on the pods during direct combining compared to losses (4.5%) due to the combine’s settings. Raman et al. (2014) observed a narrow genetic diversity of genes that control resistance to pod shattering in canola. The authors attributed it to failure to retain these traits during the domestication and selection process, which could also be applicable to camelina. Chandler et al. (2005) identified a gene (the MADSB transgene) that results in rigid siliques and prevents precocious seed dispersal in oilseed rape compared to the wild-type. Child et al. (1998) reported that small amounts of ethylene can trigger separation in the cells of the dehiscence zone of oilseed seed rape when indole-3-acetic acid levels are low. These studies demonstrate the potential of utilizing molecular techniques to develop camelina cultivars that can withstand shattering.

Our findings suggest an early harvest will increase camelina SY. However, this requires swathing, which can increase the total production cost. When camelina is direct combined at early harvest, approximately 50% of the immature pods will not thresh, which contributes to SY loss. At mid-harvest, 25% of the immature pods plus 9.5% as a result of delayed harvest (total of 34.5%) will contribute to SY loss. Nonetheless, oil content was greatest at mid-harvest, which compensates for the SY loss. Although an average of a 23.6% SY loss was observed when harvested late with pruners, the pods were very dry at that stage. Hence, mechanical disturbance imposed on the pods during direct combining may result in greater SY loss. Additionally, estimated biodiesel yield was the lowest at late harvest. It is important to note that actual SY loss would depend on the type of combine and combine settings. Installing a 0.357-cm screen over the lower sieves of the combine has been recommended to provide a good separation of the stem pieces and pods (Enjalbert and Johnson, 2011; Hunter and Roth, 2014; Sintim, 2014). Seed yield loss from threshing with a portable thresh after harvesting with pruners, as performed in this study, may not be equivalent to swathing in commercial fields (Haile et al., 2014).

Currently, the processing of camelina seeds for biodiesel and the by-products for animal feed are the major uses; although, research efforts are being focused toward optimizing epoxidation of camelina oil for industrial applications, such as resins, adhesives, and coatings (Kim et al., 2015; Obour et al., 2015; Reddy et al., 2012). As such, SY and oil content are key determinants of camelina productivity to producers and these conditions were favored at mid-harvest.

CONCLUSIONS

Delaying harvest until when more than 90% of camelina pods were ripe resulted in an average of 23.6% greater SY loss due to pod shattering compared to early harvest when 50% of the pods were ripe. The SY loss from direct combining was 11.7%, which was attributable to the mechanical disturbance imposed on the pods and the combine settings. While the current study shows that an early harvest will increase camelina SY, this process will require swathing, which may increase the total production cost. Seed yield and oil content are key determinants of camelina productivity to producers and these conditions were favored at mid-harvest. Further studies aimed at developing new cultivars that are resistant to pod shattering or combine harvester specially adapted for harvesting small seed crops such as camelina would be very important steps toward increasing commercialization of camelina’s seed production.

ACKNOWLEDGMENTS

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