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Comparison of several *Brassica* species in the north central U.S. for potential jet fuel feedstock☆

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ABSTRACT

Hydrotreated renewable jet fuel (HRJ) derived from crop oils has been commercially demonstrated, but full-scale production has been hindered by feedstock costs that make it more costly than petroleum-based fuels. Maintaining low feedstock costs while developing crops attractive to growers will be key to producing affordable HRJ and creating a dependable supply. Several Brassica oilseed species could potentially serve as feedstock, but genotypes agronomically and economically well suited for a given region will likely vary with environment and current cropping systems. The objectives of this study were to evaluate seed and seed oil yields of 12 summer annual Brassica genotypes representing six different species [*Brassica napus* L., *Brassica rapa* L., *Brassica juncea* L., *Brassica carinata* L., *Sinapis alba* L., and *Camelina sativa* (L.) Crantz.] and identify environmental factors that might limit their growth and oil production. The study was conducted during 2013 and 2014 in west central Minnesota, U.S. on a Barnes loam soil. This study is part of a larger project focused on evaluating the same set of oilseeds across the major wheat (*Triticum aestivum* L.) growing areas of the U.S. Seed yields for the 12 spring-sown crops in Minnesota ranged from 1058 to 3718 kg ha^{-1} in 2013 and 515 to 2020 kg ha^{-1} in 2014. The range in seed oil yield was 287–1588 kg ha^{-1} in 2013 and 210–885 kg ha^{-1} in 2014. Plant lodging was a serious issue in 2013, but it varied widely among genotypes. In 2014, which was characterized by an abnormally wet spring, disease infection {most likely white leaf spot [*Pseudocercosporella capsellae* (Ellis & Everh.) Deighton 1973]} and flea beetle [*Phyllotreta cruciferae* (Goeze)] feeding led to plant damage, but these were primarily confined to certain *Brassica napus* cultivars. In west central Minnesota, certain *B. napus* canola lines and *B. carinata* produced the greatest seed and oil yields. *B. carinata* was the latest maturing species in the study, produced the highest biomass, and tended to have low harvest indices, indicating ample room for yield improvement. For any given ecoregion, striking a balance among crop yield, agricultural input costs, and optimum species/cultivar choice for a particular cropping system will be important for providing a reliable and affordable feedstock for HRJ.

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1. Introduction

Hydrotreated renewable jet fuel (HRJ) derived from crop oils has been commercially demonstrated. In addition, American Society for Testing and Materials standards (ASTM) have been developed for HRJ fuel and since 2011 it has been approved for commercial aviation use. Nevertheless, full-scale production of HRJ has yet to be demonstrated, primary because it is not yet cost competitive with petroleum-based fuels. The majority of the cost for producing biofuels from plant-derived oils is the cost of producing the feedstock itself, which can represent 80% or more of the total biofuel production cost (Demirbas, 2006).

A strong commitment by the commercial aviation industry and the U.S. Department of Defense exists for advancing HRJ and other drop-in alternative fuels. For instance, the commercial aviation industry has set a goal of carbon neutral growth by 2020 and reducing petroleum jet fuel use 50% by 2050 (IATA, 2009). Because there are few renewable fuels options for aviation use, agriculture is faced with an excellent opportunity to fill this niche with the production of industrial oilseed crops (Fishel et al., 2011). Ultimately, the reduction in the cost of producing HRJ will likely come from reducing costs at multiple stages along the entire biofuel supply chain. However, lowering feedstock production costs presently allows the greatest amount of room for improvement. Reducing feedstock costs while developing crops attractive to farmers will be key to producing affordable HRJ and creating a dependable feedstock supply.

Other important factors to consider in developing affordable HRJ include selecting suitable oilseed feedstock that minimize competition for food and feed production (Johnson et al., 2007), while also fitting well into present cropping systems to promote environmental and economic sustainability. Several species from the Brassicaceae (mustard) family can serve as feedstock for HRJ, and some such as *Brassica napus* are already being used for biodiesel manufacturing in several countries. Moreover, research indicates Brassica oilseed crops provide many rotational benefits when used as a “break” or rotational crop in small grain cropping systems, especially those emphasizing wheat production (Kirkegaard et al., 2008). Benefits of rotating Brassica oilseeds in small grain systems include improved soil structure (Chan and Heenan, 1996), increased yields and protein content of wheat (Gan et al., 2003), improved soil N cycling (Ryan et al., 2006), and reduced pathogen incidence (Kirkegaard et al., 2008). Although more effort has gone into the research and development of *B. napus* and *Brassica juncea* for food and industrial use, other Brassicaceae relatives such as camelina, *Brassica carinata*, and *Sinapis alba* also show promise as potential HRJ feedstocks.

These alternative crops have attributes that may make them more suitable as biofuel feedstock for a given agricultural region than canola or rapeseed. For instance, camelina tends to require less N than canola for attaining optimum yields (Wysocki et al., 2013; Sintim et al., 2015), has good drought and disease resistance (Lenssen et al., 2012), and certain winter genotypes are highly freeze tolerant (Gesch and Cermak, 2011). Recent efforts are underway by the Canadian government to develop *B. carinata* (Ethiopian mustard) as a jet fuel feedstock adapted to cool short-season environments (Taylor et al., 2010). Research on *B. carinata* has shown that it can compete yield-wise with *B. napus* while producing industrial quality oil rather than that for food use (Pan et al., 2012). Likewise, *S. alba* is well adapted to cool short-season environments and has been considered as a potential feedstock for advanced biofuels (Blackshaw et al., 2011).

Because Brassica oilseed crops typically fit well in small grain cropping systems, the areas within the U.S. having the greatest potential for expansion of oilseed production for HRJ and other advanced biofuels, may be the rain-fed wheat producing regions (Pavlista et al., 2011). The primary wheat growing regions of the U.S. include the Pacific Northwest, northern Great Plains, and Central Plains regions (USDA-NASS, 2015). The present study was conducted in west central Minnesota, which is located on the eastern edge of the northern Great Plains region. The objectives of the study were to evaluate seed and seed oil yields of 12 summer annual Brassicaceae genotypes representing six different species and assess environmental effects on plant growth and yield. This study is part of a larger project encompassing eight experimental locations distributed across the primary wheat growing regions of the U.S. that are evaluating the same set of Brassica genotypes.

Table 1
Description of the Brassica genotypes used in the study.

Specie	Cultivar	†Oil type	Growth habit
Brassica napus	DK3042 RR	Canola	Spring
Brassica napus	Gem	Industrial	Spring
Brassica napus	Invigor L130	Canola	Spring
Brassica napus	SC28	Canola	Spring
Brassica rapa	Eclipse	Canola	Spring
Brassica juncea	Oasis	Canola	Spring
Brassica juncea	Pacific Gold	Industrial	Spring
Brassica carinata	AAC A110	Industrial	Spring
Brassica carinata	080814 EM	Industrial	Spring
Camelina sativa	CO46	Industrial	Spring
Sinapis alba	Idagold	Industrial	Spring
Sinapis alba	Tilney	Industrial	Spring

†Oil type refers to whether the seed oil is food grade (Canola) or industrial grade (Industrial), which is high in euricic acid and glucosinolates.

We envision that no one agricultural region, or for that matter oilseed genotype, will meet all the feedstock requirements for HRJ production, and further hypothesize that the highest yielding or best performing genotype(s) will differ across regions. Maintaining adequate feedstock supply to sustain the future needs of the aviation industry will likely require a portfolio of oilseed choices and diversity of growing environments.

2. Materials and methods

2.1. Cultural practices

The present study was conducted during the growing seasons of 2013 and 2014 at the USDA-ARS Swan Lake Research Farm located near Morris, Minnesota (45° 35′N, 95° 54′W; 344 m elevation). The soil was a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll). Soil samples from the study area were taken in the spring prior to sowing. In the top 60 cm of the soil profile, the pH ranged from 7.8 to 8.6, total inorganic and organic carbon ranged from 18.4 to 43.0 g kg^{-1}, and total nitrogen ranged from 0.7 to 2.3 g kg^{-1}.

The experimental design was a randomized complete block replicated four times and the previous crop both years was spring wheat. The size of each individual sub-plot was 3.6 m by 7.6 m. The summer annual Brassica genotypes are listed in Table 1.

All Brassica genotypes were sown on 7 May in both years of the study. For the species used in this study, the optimum sowing time is as early as possible in the spring, similar to that of spring wheat, which is typically from mid-April to mid-May in the region where the study was conducted. Seeds were sown on 30 cm spaced rows using a Wintersteiger plot drill (Model PDS 12R) with double-disk openers and using a seeding depth of 1.0 cm for camelina and 2.0 cm for all other genotypes. A similar live seed rate of 1.48×10^6 seeds ha^{-1} was used for all genotypes except camelina, which was sown at 3.95×10^6 live seeds ha^{-1}. Laboratory germination tests were conducted to determine germination rate of each seed lot. Seed used in the study was obtained from either commercial sources or pure lines from personal sources. The plot

Table 2

Monthly average air temperature, and cumulative precipitation and growing degree days (GDD) in 2013 and 2014 including the 30-yr average of air temperature and precipitation at the study site. GDD were calculated using a base temperature of 4 °C.

	†Mean air temperature (°C)				Precipitation (mm)			GDD (°C d)	
Month	2013	2014	30-yr avg.		2013	2014	30-yr avg.	2013	2014
April	1.8	4.9	6.7		15	64	58	38	80
May	13.0	13.8	13.9		60	89	76	292	314
June	19.3	19.9	19.1		179	149	98	456	479
July	22.2	20.5	21.5		57	33	100	558	510
August	21.5	20.8	20.1		49	73	84	545	528
Mean	15.6	16.0	16.3	Total	360	408	416	1889	1911

†Climate parameters were measured at an automated weather station within 150 m of the study site.

area for the Brassica genotypes was cultivated (10 cm depth) in the spring and then harrowed (5 cm depth) prior to sowing. Fertilizer was broadcast at a rate of 135–45–45–22 kg ha^{-1} of N–P–K–S on the *B. napus* and *rapa* plots, 114–38–38–19 kg ha^{-1} of N–P–K–S on *S. alba* plots, and 90–34–34 kg ha^{-1} of N–P–K on camelina plots. All plots received trifluralin at a rate of 1.1 kg ai ha^{-1} to control weeds and both herbicide and fertilizer were incorporated with the tillage events. Cultural practices including fertility, planting, and pest control were based on best management practices developed and published in growers' guides by academia and industry (Boyles et al., 2012; Grady and Nleya, 2010; Agrosoma Biosciences Inc., 2012). The management practices chosen for use in this study were done so to try and optimize yields for each oilseed species for the given region in an effort to minimize the influence of agricultural management on crop yield differences and gain a better understanding of environmental effects on crop growth and yield. However, it should be noted that crop performance could be biased, at least to some degree, by either managing the species all the same or by optimizing individual species performance.

Except for the initial treatment of plots with trifluralin, no other pesticides were used in 2013. However, in 2014, due to a severe flea beetle infestation (late May to early June), all plots were treated on 30 May with malathion, diethyl [(dimethoxyphophino-thioyl) thio] butanedioate at a rate of 0.37 L ai ha^{-1}. Three of the genotypes, the two *B. juncea* cultivars (Oasis and Pacific Gold) and the *B. napus* cultivar Gem, were treated a second time on 6 June with malathion at the same rate.

2.2. Plant sampling and measurements

Seedling emergence was measured after sowing until plant populations stabilized on three randomly chosen 1-m strips in each of the plots for all genotypes. Plant lodging was visually assessed on a scale of 0–5 on all plots at harvest, with 0 referring to fully erect and 5 being parallel to the soil surface.

Just prior to harvesting plots for seed yield, a 1-m length of row from each plot was sampled outside the seed harvest area but inside the border rows for determining total above-ground biomass yield. These samples were placed in a forced air oven at 65 °C until constant weight was achieved. Dried plant samples were weighed before being threshed and the seed cleaned and weighed. Harvest index (HI) was calculated as the fraction of clean dry seed to total above-ground dry biomass. The center six rows from each plot were harvested for seed yield with a mechanical plot harvester. Seeds were brought back to the lab where they were dried at least 72 h in a forced air oven at 45 °C before being cleaned and weighed. A subsample from each harvest sample was further dried at 65 °C until constant weight to determine moisture content and all yields were adjusted to 10% moisture for comparison. Harvest dates varied by genotype between July and August and the days from planting to harvest are presented in Table 3.

Seed oil content was determined by pulsed Nuclear Magnetic Resonance (pNMR, Bruker mq-CU 20-series, Billerica, MA, USA) using factory instrument setting 909_18A, NMR frequency 19.98 MHz at 40 °C. Seed samples (2.5 g) of each treatment replicate were placed into vials (Pyrex No. 9820) and dried at 130 °C for 3 h and then cooled in a desiccator for 15 min to record dry weights. The samples were then reheated to 40 °C for 2 h before pNMR analysis. Standard curves for pNMR were developed using *B. juncea* oil applied to tissue paper placed vials (Pyrex No. 9820). This method resulted in a standard curve with a 0.99 correlation coefficient. Seed oil yields were calculated using the harvested dry seed yield (kg ha^{-1}) multiplied by oil content.

Weather data including air temperature and precipitation were collected at a permanent weather station located within 150 m of the study site in both years. Growing degree days (GDD) were calculated as: $\text{GDD} = \sum (T_{\text{max}} + T_{\text{min}}/2) - T_{\text{base}}$, where T_{max} and T_{min} are daily maximum and minimum air temperature, respectively, and T_{base} is base temperature of which a value of 4 °C was used, which is commonly used for Brassica crops (NDAWN, 2014).

2.3. Statistical analysis

Data were analyzed by ANOVA using the Mixed Procedure of SAS (SAS for Windows 9.1, SAS Inst., Cary, NC). All data except for seed oil content were affected by year and therefore, were analyzed separately by year. For the mixed model, cultivar was treated as a fixed effect and replication as a random effect. Seed oil content was analyzed across both years and year and replication were treated as random effects. Mean comparisons were made by least significant difference (LSD) using the Bonferroni adjustment for mean separations at the $P \leq 0.05$ level.

3. Results and discussion

3.1. Climate conditions

From spring thaw (April) until final crop harvest (August), the mean growing season temperature was 0.7 and 0.3 °C cooler than the 30-yr average in 2013 and 2014 (Table 2). Average air temperatures in both years were considerably cooler in April, but then tended to be warmer in July and August than the 30-yr average. In 2013, total precipitation was 56 mm below normal, while it was near normal in 2014. The distribution of rainfall during both growing seasons was abnormal, with unusually high amounts of precipitation accumulating in June, when most of the Brassica genotypes in the study were either in late vegetative phase of growth or just beginning to enter reproductive phase (late June). In 2014, from April through June, conditions were unusually wet, followed by an abnormally dry July. The number of accumulated GDD throughout the growing season was similar in both years (Table 2).

Table 3
Comparison of seed and biomass yield, harvest index (HI), days from planting to harvest (DH), lodging score (LS) and plant population density (PPD) following emergence for the Brassica genotypes studied in 2013 and 2014. Values are means, $n = 4$. Values within columns followed by the same letter are not significantly different at the $P \leq 0.05$ level.

	2013							2014					
Cultivar	Specie	Yield kg ha^{-1}	†Biomass kg ha^{-1}	HI relative	DH d	LS	PPD plant m^{-2}	Yield kg ha^{-1}	Biomass	HI relative	DH d	LS	PPD plant m^{-2}
Invigor L130	*B. napus*	3718 a	8928 b	0.39 abc	99	0.8 de	172 b	1904 a	5821 bcd	0.35 a	98	0.3 c	72 abc
080814 EM	*B. carinata*	3604 ab	15905 a	0.33 c	113	0.0 e	98 bc	1980 a	11250 a	0.29 abc	111	0.3 c	64 abc
AAC A110	*B. carinata*	3299 ab	17908 a	0.37 abc	113	2.3 bcd	117 bc	2017 a	10541 ab	0.28 abc	111	0.3 c	41 c
Pacific Gold	*B. juncea*	2925 abc	6665 bc	0.42 ab	99	2.0 cde	100 bc	2011 a	7818 abc	0.33 abc	98	1.3 abc	39 c
DK3042 RR	*B. napus*	2765 bcd	7911 bc	0.45 a	99	3.0 abc	139 bc	2019 a	5903 bcd	0.35 a	98	0.8 bc	62 abc
Gem	*B. napus*	2338 cde	7708 bc	0.40 abc	99	4.8 a	132 bc	515 c	3037 cd	0.26 c	97	2.5 a	42 c
SC28	*B. napus*	2254 cde	7665 bc	0.40 abc	99	4.3 ab	133 bc	514 c	2419 d	0.26 c	97	1.3 abc	63 abc
Oasis	*B. juncea*	2226 cde	6631 bc	0.38 abc	99	3.0 abc	162 bc	1462 ab	4448 cd	0.34 ab	97	0.3 c	48 bc
Tilney	*S. alba*	2022 de	9197 b	0.34 c	106	2.5 bcd	143 bc	1061 bc	4509 cd	0.32 abc	93	0.1 c	80 abc
Eclipse	*B. rapa*	1567 ef	5718 bc	0.43 ab	93	2.5 bcd	87 c	821 bc	3051 cd	0.29 abc	93	1.8 ab	45 bc
Idagold	*S. alba*	1156 f	7773 bc	0.36 bc	93	2.5 bcd	121 bc	913 bc	5284 bcd	0.26 c	93	0.0 c	91 ab
CO46	*C. sativa*	1058 f	3963 c	0.34 c	84	0.0 e	252 a	778 bc	2304 d	0.27 bc	89	0.0 c	107 a

†Biomass and HI were determined from whole plant samples taken from a 0.3 m^2 area from each plot prior to harvest.

3.2. Seed and biomass yields

Seed yields in 2013 ranged from 1058 to 3718 kg ha^{-1}, while they ranged from 514 to 2017 kg ha^{-1} in 2014 (Table 3). Although climatic conditions were somewhat similar between years (Table 2), the unusually wet cold spring and early summer of 2014 likely contributed to generally lower yields. Although reports vary, there is clear evidence indicating that plant growth and yields of some Brassicaceae-related oil crops are negatively affected by excess soil moisture (Gutierrez Boem et al., 1996; Gesch and Cermak, 2011). Lower seedling emergence in 2014 compared to 2013 (Table 3) also may have contributed to lower seed yields. The emergence of most genotypes in 2014 was about half of what it was in 2013 although the sowing rate of live seed was the same in both years. Again, the wet spring in 2014 may have been responsible for the poorer emergence compared to 2013. During 2013, most of the spring genotypes exhibited similar emergence except for CO46 camelina, which was considerably greater but was seeded at a much higher rate than the other genotypes (Table 3).

Despite generally much greater seed yields in 2013 than in 2014, with little exception, the highest and lowest yielding genotypes were similar over both seasons (Table 3). The *B. napus* canola cultivars Invigor L130 and DK3042 RR, the two industrial *B. carinata* lines 080814 EM and AAC A110, and *B. juncea* cultivar Pacific Gold consistently yielded the highest both years. Invigor L130 and DK3042 RR are commercial lines that are commonly grown in the U.S. and Canada, so it was not surprising that they performed well. However, *B. carinata*, which has more recently undergone development as a biofuel feedstock in North America performed as well or better than the *B. napus* and *B. juncea* genotypes in the present study. Similarly, Pan et al. (2012) reported that several recently developed *B. carinata* cultivars preformed as well or better than a common commercial line of *B. juncea* (AC Vulcan) across a diversity of environments in Canada. Conversely, Blackshaw et al. (2011) found that *B. carinata* did not perform as well as several other Brassica species in the Prairie Province region of Canada. However, in that study, an older common germplasm line was used that may not have been as well adapted to the given environments as the newer lines used in the Pan et al. (2012) study.

The genotypes that were consistently low yielding were camelina (CO46), *S. alba* (Idagold), and *B. rapa* (Eclipse) (Table 3). The seed yields for camelina, which were 778 kg ha^{-1} in 2014 and 1058 kg ha^{-1} in 2013, were generally lower than previously observed at the study site, especially when seeded in early May. In west central Minnesota, Gesch (2014) reported that average seed yields of 10 spring camelina cultivars over a three year period ranged from 1160 to 1862 kg ha^{-1} when sown between 16 April and 15 May, with cultivar CO46 yielding as high as 2073 kg ha^{-1}. The low yields of CO46 in the present study were likely due to extremely wet spring conditions, which have been clearly shown to hamper stand establishment and plant growth of camelina (Gesch and Cermak, 2011).

In the present study, the two *B. napus* cultivars, Gem and SC28 performed quite differently between years (Table 3). In 2013, their seed yields were intermediate at 2254–2338 kg ha^{-1}, while in 2014 they both had the lowest yield at about 515 kg ha^{-1}. The decline in yield in 2014 resulted from a severe disease infection early in the 2014 growing season. The disease symptoms observed included shriveling of leaves with large brown lesions, stunted plant growth, and crooked stems. Other genotypes including Invigor L130 and CO46 camelina were also infected, but not as severely and symptoms tended to be contained to only lower mature leaves early in the growing season. Invigor L130 and CO46 eventually outgrew the symptoms, while Gem and SC28 remained stunted throughout most of the season. Although the disease was not positively identified, pictures of symptomatic plants were sent to an expert (D. Fernando, personnel communication) who indicated that it was most likely white leaf spot caused by *Pseudocercosporella capsellae*, which can be exacerbated by wet conditions and extreme rain events as was experienced in late May and June of 2014 at the study site. Differences were observed in resistance to the pathogen. For instance the *B. carinata*, *B. juncea*, and *S. alba* genotypes were little affected. No instances of disease were observed in 2013 for any of the genotypes in the study.

The two *B. carinata* genotypes had the greatest total biomass production in both years. In 2013, when averaged across both cultivars, biomass production of carinata was 46% greater than Tilney (*S. alba*), which produced the next highest biomass (Table 3). Genotypes with the greatest biomass production did not necessarily produce the highest seed yield. For instance, biomass yields of the two *S. alba* genotypes were similar to those for Invigor L130 and DK3042 canola but had lower seed yields and hence lower HI. Although both biomass and seed yield were reduced during 2014, yield was reduced relatively more than biomass, and therefore, HI values were lower in 2014 (Table 3). The high biomass yield of 080814 EM and AAC A110 *B. carinata* coupled with a relatively low HI suggests that there is ample room for yield potential and thus, HI improvement in *B. carinata*.

Both of the *B. carinata* cultivars were the latest genotypes to mature (i.e., days from planting to harvest; Table 3). Furthermore, there was a tendency for the earliest maturing Brassica species (i.e., *S. alba*, *B. rapa*, and *Camelina sativa*) to be lower yielding than later maturing genotypes. This response may be similar to that seen in crops such as soybean [*Glycine max* (L.) Merr.] where there is a wide range in maturity among genotypes with a tendency for longer maturing cultivars to produce higher yields and biomass when grown under a similar environment and management system (Edwards and Purcell, 2005).

In both 2013 and 2014, flea beetle feeding during rosette to bolting stage of several genotypes was observed, but in 2013 it was minimal and therefore, no action was taken to control this pest. In 2014, damage to some of the genotypes, particularly Gem and SC28 *B. napus*, was extensive enough to warrant insect control. Incidentally, flea beetle feeding on Gem and SC28 plants in 2014 may have made them more susceptible to white leaf spot disease (D. Fernando, personnel communication). Moreover, flea beetle feeding may have contributed to the lower seed yields in 2014.

Considerable plant lodging was observed in 2013 and differences in susceptibility were noted among genotypes (Table 3). In 2013, lodging of some genotypes was severe enough that it may have affected yields. During 2013, Gem and SC28 showed the greatest degree of lodging while the two camelina cultivars and Invigor L130 (*B. napus*) and 080814 EM (*B. carinata*) showed the least. In 2014, lodging was not a major issue, but Gem still showed a greater degree of lodging than most other genotypes (Table 3). The lodging in 2013 occurred in late June and early July during two severe storms that produced wind speeds ≥ 18 m s^{-1}. At this time most genotypes were flowering or beginning to flower except for the two carinata cultivars. Plants that were affected were bent over by the wind, but not uprooted or broken at the stem. Even the most severely affected cultivars (Gem and SC28) continued to flower and eventually set seed that was able to be harvested with small plot-scale machinery. However, on a larger farm-scale level, these plants would likely have been problematic to harvest.

Although the present study specifically reports yield information for Morris, Minnesota, seven other locations are testing the same set of Brassica genotypes. These locations include Akron, Colorado; Moscow, Idaho; Ames, Iowa; Sidney, Montana; Mandan, North Dakota; Pendleton, Oregon; and Temple, Texas. As hypothesized, it is likely that the highest and lowest yielding Brassica genotypes at any given experiment site will differ due to different soil characteristics, climatic conditions, and diseases and pests. The seed yield results of the same set of genotypes grown at all eight research sites were ranked from highest to lowest (data not shown). As expected, the highest and lowest yielding genotypes tended to differ across environments. When the rankings were average across all sites for 2013 and 2014, the two common commercial lines of canola, DK3042 (DeKalb) and Invigor L130 (Bayer Crop Sciences) tended to be the highest ranking in yield performance. The *B. carinata* cultivar 080814 EM also performed well indicating that significant progress is being made in its development as a biofuel feedstock for North America (Pan et al., 2012). Conversely, the *S. alba* cultivar Idagold and *B. napus* cultivar Gem were consistently low yielding across sites. Camelina (CO46) is an interesting example of a genotype that shows good yield potential, but may not be as widely adapted to a large geographical range. Camelina tended to be either the highest or lowest yielding genotype depending on the location it was grown. Research efforts are currently underway to elucidate some of the environmental factors affecting these yield results. This information will be useful in both targeting the best suited genotypes for a given environment as well as identifying traits for growth and yield improvement.

3.3. *Seed oil content and yield*

Despite differences in seed yield between years, oil content did not differ and therefore, was combined across years for analysis. The common commercial cultivars of *B. napus* canola DK3042 and Invigor L130 had the highest oil contents (Table 4). Again, this is not surprising since much breeding effort has gone into these cultivars to improve seed yield and oil content. The two *B. carinata* cultivars, which were consistently among the highest seed yielding (Table 3), tended to have only intermediate to low oil contents at 42 and 38%, for AAC A110 and 080814 EM, respectively (Table 4). The *S. alba* cultivars Tilney and Idagold by far shared the lowest oil content at 28%. *S. alba*, commonly known as white mustard, is best known for its use as a condiment and for culinary purposes, but has been considered as a potential feedstock for industrial uses including biofuels (Yaniv et al., 2002).

Table 4
Seed oil content (% wt wt^{-1}) of cultivar/species averaged over both years of the study and seed oil yields in 2013 and 2014. Values of oil content are means, $n = 8$ and for oil yield are means, $n = 4$. Values within columns followed by the same letter are not significantly different at the $P \leq 0.05$ level.

			Oil yield (kg ha^{-1})	
Cultivar	Species	% Oil content	2013	2014
DK3042 RR	*Brassica napus*	48.2 a	1228 bc	885 a
Invigor L130	*B. napus*	47.1 ab	1588 a	830 a
Gem	*B. napus*	45.4 bc	990 bcd	210 c
Oasis	*B. juncea*	45.1 bc	914 cde	608 ab
Eclipse	*B. rapa*	43.9 cd	611 ef	341 bc
AAC A110	*B. carinata*	42.2 de	1284 ab	778 a
SC28	*B. napus*	41.8 de	869 de	199 c
Pacific Gold	*B. juncea*	40.8 e	1037 bcd	790 a
080814 EM	*B. carinata*	38.1 f	1293 ab	674 a
CO46	*C. sativa*	37.3 f	351 f	276 c
Tilney	*Sinapis alba*	28.1 g	511 f	278 c
Idagold	*S. alba*	28.1 g	287 f	237 c

One the most important attributes of potential oilseed feedstock for jet fuel production is total seed oil yield. However, it is important to point out that large-scale commercial production of feedstock for HRJ will also greatly depend on profitable markets for the seed meal byproduct following oil extraction. Amongst the genotypes studied, oil yield ranged from 287 to 1588 kg ha^{-1} in 2013 and from 210 to 885 kg ha^{-1} in 2014 (Table 4). Despite lower seed oil content than some of the other Brassica species such as *B. napus, B. rapa,* and *B. juncea*, the *B. carinata* cultivars (080814 EM and AAC A110) tended to be among the highest oil yielders in the study (Table 4). The genotypes that consistently yielded the lowest were those of camelina and *S. alba*. Similarly, Blackshaw et al. (2011) demonstrated that *S. alba* is relatively low oil yielding compared to other Brassica oil crops, when grown across the Canadian prairie provinces. Although it was one of the lowest yielding genotypes in the study, CO46 camelina tended to be one of the most consistent in terms of seed and seed oil yield between years (Tables 3 and 4). Less attention has been given to improving the seed yield and oil content of camelina than other species such as *B. napus*. Recently, certain cultivars of camelina have been shown to have excellent freeze tolerance (Gesch and Cermak, 2011), and thus, may have good potential to be used as a cash cover crop in dual cropping systems (Gesch and Archer, 2013).

4. Conclusions

This study demonstrates the diversity of seed and seed oil yield response among different Brassica oilseed species when grown in west central Minnesota located in the north central region of the U.S. In Minnesota, the genotypes showing the greatest potential in this study for producing the highest amount of seed oil for biofuel feedstock were *B. napus* (Invigor L130 and DK3042 RR), *B. carinata*, and *B. juncea* (cv. Pacific Gold), while the lowest yielding were *S. alba* and camelina. More research, however, is needed to determine the causes for these differences so that in the near future better decisions can be made for targeting a given species/cultivar for production in a given region. Also, this information will identify traits that will benefit future breeding efforts to further improve those genotypes showing the greatest potential for HRJ feedstock to make them better adapted to a wider range of environments.

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