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The evaluation of cool-season oilseed crops for yield and adaptation in texas: an approach for selection of efficient biofuel feedstock

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Abstract

Expansion of the biofuel industry will require identification of suitable feedstock for particular geographic regions and optimization of production capacity by enhancing research-based management practices. To identify potential biofuel feedstocks, numerous cool-season oil-seed crops were evaluated for their yield potential and quality in Texas; forty-five genotypes of four winter and spring-type oilseed crops were evaluated at nine Texas A&M AgriLife Research and Extension Centers across the state. All trials were evaluated under low input rain-fed conditions. Spring rapeseed and safflower were the highest yielding crops with yields reaching 1372 kg ha^{-1} and 1240 kg ha^{-1}, respectively. The oil content of safflower was lower than all other evaluated crop species. In South and Central Texas, fall seeded flax yields averaged 1075 kg ha^{-1} with an average oil concentration of 38.3 % (w/w); however, flax yields were low at all North Texas locations. Camelina yields, 473 kg ha^{-1}, were lower than other evaluated crops, especially in South and Central Texas. Several cool-season oil-seed crops would be considered economically competitive with other winter grown small grain crops in Texas.

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Introduction

Finding alternate renewable fuels for the replacement of fossil fuels is necessary for global energy sustainability in the future. The global petroleum and crude oil consumption has reached about 89 million barrels per day in 2012 (United States Energy Information Administration, 2012). The continuous uptrend of the global population and industrialization will impose an additional demand of 8.5 million barrels per day from 2015 to 2030 (United States Energy Information Administration, 2011). Currently, the United States alone consumes about 19 million barrels of fuel per day (21% of total world consumption) and is expected to reach a cumulative consumption of 22 million barrels per day by 2035 (United States Energy Information Administration, 2011). China is expected to consume 17 million barrels per day by the end of 2035 (United States Energy Information Administration, 2011).

Texas is one of the largest biodiesel processing states in the U.S. with a current contribution of 14% (State Energy Conservation Office, 2007) and has the capacity to expand even further. The current biodiesel and glycerol production capacity of Texas has reached 456 million gallons (United States Energy Information Administration, 2011). However, the availability of soybean and other oilseed crops from Texas is limited, and soybean (*Glycine max* L.) oil is imported into Texas processing facilities from the mid-western states. To minimize the excessive economic costs resulting from importing feedstock, localized production of feedstock suitable to Texas is necessary. Identifying the most productive local feedstock for biofuel production is a key step in increasing the Texas economy and meeting the future demand for U.S. biofuel production. The production potential of various cool-season oilseed crops for replacing soybean were extensively studied in several regions of US for their yield and adaptation. Some of those oilseed crops include flax *(Linum usitatissinum* L.*)*, safflower *(Carthamus tinctorius* L.*)*, canola *(Brassica spp.)*, and camelina *(Camelina sativa* L.*)*.
Flax is originated in Mediterranean and Southwest Asia regions (Millam *et al.* 2005). North Dakota is the leading state in flax production with an average yield of 1232 kg ha^{-1} with over 156,000 harvested hectares (USDA-NASS, 2011). Variety yield trials conducted in North Dakota in 2010 reported a flax yield range of 358 kg ha^{-1} to 2744 kg ha^{-1} and an average yield of 1047 kg ha^{-1}. Flax production in Texas started in the early 1900's and peaked in 1949 with 133,198 hectares in production (USDA-NASS, 2011). In Texas, the most popular varieties from 1960 to 1970 yielded a maximum of 1120 kg ha^{-1} (Hodges *et al.*, 1970). However, most of the flax production at that time was non-irrigated and limited to the Southern Blacklands and Coastal Bend region of the state. The national 5-year average yield of flax from 2007 to 2011 was 1186 kg ha^{-1} (USDA-NASS, 2011).

Safflower is one of the drought tolerant oil seed crops (Kephart *et al.*, 1990). Results from the Pacific Northwest indicate that spring safflower yields ranged from about 720 to 2200 kg ha^{-1}, and oil concentration ranged from 19 to 37% under dryland conditions in Idaho (Auld *et al.*, 1978). Similar results were reported in Southern Alberta, where spring planted safflower yields ranged from 1120 to 1340 kg ha^{-1} (Mundel, 1981). A variety trial conducted at North Dakota State University revealed that spring safflower yields ranged from 1724 to 2032 kg ha^{-1} with oil concentrations ranging from 38 to 44% (Berglund *et al.*, 2007). In California, the average yield of spring safflower for 2011 was 1692 kg ha^{-1} (USDA-NASS, 2011). Irrigated safflower yields ranged from 1120 to 4480 kg ha^{-1} in Washington (Nelson, 1964) and the national 5-year average yield of safflower in 2011 was 1387 kg ha^{-1} (USDA-NASS, 2011).

Variety trials conducted in North Dakota in 2010 indicated that canola yielded as high as 3920 kg ha^{-1} with an average high oil concentration of 44.8% (Kendel, 2010) and an average yield of about 2016 kg ha^{-1}. A national winter rapeseed trial conducted in the Southern Great Plains in 2011 reported an average yield of 1892 kg ha^{-1} in Oklahoma, 2470 kg ha^{-1} in Kansas, and 1536 kg ha^{-1} in Texas (Stamm *et al.*, 2012). The national 5-year average yield of canola from 2007 to 2011 was 1539 kg ha^{-1} (USDA-NASS, 2011).

Agronomic trials conducted at the University of Minnesota for over 30 years resulted in exploration and establishment of camelina in the U.S. as an oilseed crop (Robinson, 1987). Yield of camelina ranged from 600 to 1,700 kg ha^{-1} at Rosemount, MN (Putnam *et al.*, 1993). However, the yield potential of camelina has remained static over many years since its introduction into the U.S. German plant breeders found transgressive segregation over parental lines in many yield traits for camelina, demonstrating both the high yield potential and capacity for yield improvement in this species (Seehuber *et al.*, 1987). In Montana, it was reported that camelina yielded 330 to 1,700 kg ha^{-1} depending upon the available moisture conditions (McVay and Lamb, 2008).

Considering a large area of under-utilized acreage in Texas and proximity to the biodiesel-processing industry for the utilization of feedstock, the production potential of these four important cool-season oil seed crops for their yield and oil was evaluated in different agro-climatic zones of Texas. Moreover, under Texas climatic conditions, where the temperatures are normally high during the late-spring season, manipulation of microclimate by irrigation and decreasing the canopy temperatures would benefit the oil quantity and quality in oilseed crops. The main objectives of the study were to: (1) identify the adaptation of flax, rapeseed, safflower, and camelina to various cropping environments in Texas, ranging from a humid subtropic (Weslaco) environment to the semi-arid temperate (Amarillo/Etter) environment and (2) identify the highest yielding species and/or genotypes of cool-season oilseed crops for oil production within the different production regions and crop management areas of Texas.

Materials and methods

Forty-five genotypes of four winter and spring-type oilseed crops (flax, rapeseed, safflower, and camelina) were evaluated at nine Texas A&M AgriLife Research and Extension Centers across Texas (Table 1, 2 and Fig. 1). Genotypes were selected based on performance data from various oilseed evaluation trials across the U.S., agronomic traits, and seed availability. Weather details for each individual location during tested years are compiled in Table 3. The experiments were configured in a randomized complete block design with three replications at each of the nine locations and were conducted for three growing seasons. Planting dates were site-specific with temperature and potential winter-kill representing the primary factors. In the south and southeast locations (College Station, Beaumont, Beeville, Uvalde, and Weslaco), both the spring and winter-type genotypes were planted in the fall (October-December). In North Texas locations, Prosper, Vernon, Amarillo, and Lubbock, winter-types were planted in fall, while spring-types were planted in late-winter or early spring. The seeding rates were 39, 5.6, 30, and 5.6 kg ha^{-1} for flax, rapeseed, safflower, and camelina respectively. Fertilizer recommendations and other management practices varied by location, but were based on best management strategies known for these crops.

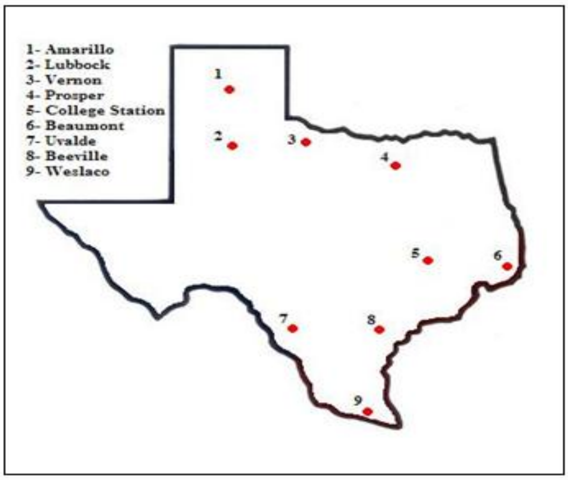

Fig. 1. Cool-season oilseed testing locations in Texas during 2007-2010.

Important management practices and production constraints

Weslaco

The trials were non-irrigated and were planted on October 23, November 18, and November 4 for each production seasons in 2007, 2008, and 2009, respectively. The management practices followed the best management practices known for each of these species in the Rio Grande Valley. Weeds, diseases, and insects were adequately managed to prevent minimal yield loss during all growing seasons. However, powdery mildew and lodging were a problem in the late-maturing genotypes. All treatments were hand-harvested on April 1, April 15, and May 7 for three production seasons, respectively.

Beeville

Two out of three years were severely drought affected and produced low yields. In the 2009-2010 production year, no yields were obtained due to poor stands. All species and genotypes were planted on November 5 and most of the crops were harvested by mid-May. Insects and pathogens were not problematic in this location; however, poor crop stands resulted in high weed pressure in the growing season.

Uvalde

The data were not obtained in first two years due to severe drought and stand establishment problems. In the third year, some stand was established due to limited rainfall in November and December months.

Beaumont

In 2007, the study was planted on November 9 -12. Excessive soil moisture prevented a good stand and resulted in uneven emergence. In both 2008-2009 and 2009-2010, excessive soil moisture of the clayey soils in the Beaumont area forced delay of planting of the cool-season annual oilseed trials at Beaumont until spring, e.g, until February 25 in 2009 with emergence of all species completed within 10 days. Frequent rains prevented most cultural practices during crop development. Grassy weeds were the biggest problem in cropping season. Due to unfavorable rainfall conditions and subsequent weed problems, no data was obtained in all three years, with the exception of flax in 2008.

College Station

Management practices were similar in College Station for all years, unless specified otherwise. In College Station, all species were planted on November 10, 2007 for the 2007-2008 cropping season. Two planting dates were established in the cropping season 2008-2009. Winter rapeseed and winter camelina were planted on October 24, 2008 and the spring rapeseed, camelina, flax, safflower, and radish were planted November 17, 2008. Before planting, the soil was cultivated with a tandom disc followed by a culti-packer. Trifluralin was applied and incorporated on field prior to final tillage to assist in controlling winter weeds. Glyphosate was sprayed as a preplant burndown application prior to planting to eliminate the emerged weeds. All plots were planted with Hege-500 small plot planter with 7 rows and 20 cm row spacing. Rainfall was below average for the fall of 2008 and 0.64 cm of irrigation was applied, a week after each planting. The experiment was fertilized with 57 kg ha^{-1} of N (ammonium sulfate (21-0-0-24) on December 17, 2008. Fertilizer was sprayed at 140 liters per hectare using the 110-03 TeeJet tips on a 9 m Remcor Boom sprayer. Several applications of Dimethoate (insecticide) were applied at the rate of 250 ml per acre to control aphids (*Lipaphis erysimi*) based on estimated thresholds. Powdery mildew (*Blumeria graminis*) was observed on both the winter and spring rapeseed and camelina genotypes and a fungicide (propiconazole (41.8%)) was applied to these genotypes to preserve the yield potential.

In 2009-2010, all winter genotypes (except safflower) were planted on October 20, 2009. All spring genotypes and safflower were planted on November 13, 2009. Plots were fertilized with a broadcast application of 78 kg ha^{-1} N (Ammonium sulfate 21-0-0-24) on December 11, 2009. Moisture was sufficient throughout the fall and irrigation was not needed for stand establishment. All experiments were top dressed with 32-0-0 at the rate of 78 kg ha^{-1} N.

Prosper

Due to the high clay content soils, narrow tillage and planting window existed for establishing the small seeded crops. The conditions were favorable only in 2007-2008. During production year 2008-2009, trials were seeded in September into dry soil, and crop emergence did not occur until late November following the first precipitation event after planting. The late emergence predisposed the small plants to winterkill during the first freeze (below -8°C) in early December. Due to prolonged saturated soils in September through early October of 2009, winter genotypes were planted in mid-October, and an acceptable stand was not achieved. Likewise, a wet spring delayed planting of the spring genotypes until in mid-April. Adequate stands were obtained with the spring genotypes, but an extended late spring drought prevented development of many reproductive structures or yield potential.

Vernon

Vernon, the location was a non-irrigated location and stand establishment was problematic in each of the three years of the experiment. Spring planted crops failed to produce measurable seed yields due to the rapid onset of high temperatures and dry condition in all three production years. Delaying planting until adequate soil moisture was present resulted in cold soil temperatures and poor stand establishment. Cold temperatures in the stand establishment stage and high temperatures in the reproductive stage were detrimental to growth and development.

Lubbock/Pecos

At Lubbock, during the 2007-2008 cropping season, all cool-season crops were planted in the third week of September and harvested by the end of July. The winter of 2007-2008 was extremely dry and windy; these environmental conditions caused reduced yields in many of the cool- season oil seed crops. During 2008-2009, the winter mustard/HEAR lines seeded in Bailey Co. on Sept. 19 failed to establish due to dry conditions.

At Pecos, where saline irrigation and soil conditions prevail, two winter hardy safflower lines and two camelina lines were seeded on October 23, 2009. A preplant application of trifluralin was sprayed to aid in weed control. Fertilizer was applied at 67 kg of nitrogen and 35 kg of phosphorus per hectare prior to planting. A disk plow and culti-packer was used to prepare the ground for planting. All varieties were irrigated with a linear irrigation system to enhance seed germination and seedling establishment. Spring oilseed crops and varieties of rapeseed, camelina, and flaxseed were planted on March 28th. All varieties emerged but the rapeseed plots were destroyed by rabbits (*Lepus timidus* L.). Camelina and flaxseed varieties were harvested in late July.

Data analysis

The data were analyzed by using SAS (SAS Institute, 2008) software using Proc GLM procedure. Fixed effects model was applied for the estimation of mean squares and F-test significance. Due to the complexity of trials at different locations and the difference in planting seasons (fall versus spring), the mean yield for each crop species for a particular year and location was obtained by combining all the genotypes. Duncan multiple range tests were performed at 0.05 significance level to determine the differences among tested crop species across the site-years.

Results and discussion

Analysis of variance (ANOVA) for yields of tested cool-season crops during all site-years were presented in Table 4. The site-years were classified into 12 environments. Each environment was represented by a location in a particular year. Beaumont and Vernon locations were excluded from the analysis due to lack of data for those locations. The results indicated that environment, crop species, and their interaction were statistically significant ($P<0.001$). The weather conditions varied largely among the tested years and the locations had different climatic and soil conditions during the tested site years (Table 2 and 3).

Yield potential of evaluated crop species in Texas

Weslaco

Spring rapeseed yielded highest with an overall mean of 1381 kg ha^{-1}, followed by safflower with a mean yield of 1280 kg ha^{-1} (Tables 5 and 6). Camelina yielded lowest with a three year average of 160 kg ha^{-1}. The environmental factors were mostly favorable in the third year (2009-2010) compared to the first two years. Spring rapeseed had consistently higher yields compared to other cool-season crops throughout all three tested years. Spring rapeseed, safflower and flax seemed to be well adapted in this region. Camelina yields were consistently lower and did not appear to be adapted to this humid subtropic region. Based on visual observations, yield limiting factors for flax included excessive vegetative growth, an indeterminate fruiting habit, and the tendency for mature pods to dehisce.

Table 1. Cool-season oilseed species/genotypes evaluated in Texas during 2007-2010.

Species	*Variety*	*Released by*	*Species*	*Variety*	*Released by*
LEAR[a]	ARC 97003	UoA[c]	Flax	AC Carnduff	AAFC[g]
	ARC 98017	UoA		AC Emerson	AAFC
	Ericka	IAES[d]		AC Linora	AAFC
	Jetton	Unknown		AC McDuff	AAFC
	Sumner	KSU		AC Lightning	AAFC
	Wichita	UoI[e]		Carter	NDSURF[h]
	Bridger	Unknown		MacBeth	AAFC
	DKW 13-86	Monsanto		Omega	NDSURF
	DKW 13-69	Monsanto		Nekoma	NDSURF
	Sunrise	IAES		Pembina	NDSURF
	Sterling	IAES		Prairie Thunder	AAFC
	Gem	UoI		Prairie Grande	AAFC
HEAR[b]	White Bionute	UoI		Rehab-94	Unknown
	White Idagold	UoI		York	NDSU
	White Pacific Gold	UoI		Prairie Blue	AAFC
Camelina	BSX – WG2	Blue Sun	Safflower	PI-406002	TTU[i] (Exp.)
	BSX-WG3	Blue Sun		PI-544006	TTU (Exp.)
	BSX-WG4	Blue Sun		PI-544017	TTU (Exp.)
	BSX-WG5	Blue Sun		PI-388901	TTU (Exp.)
	Baltensperger	SDSU[f] (Exp.)		PI-405985	TTU (Exp.)
	BSX-WG21	Blue Sun			
	BSX-WG72	Blue Sun			
	Cheyenne	Unknown			
	Calena	Unknown			
	Celine	Unknown			

[a]LEAR- Low Euricic Acid Rapeseed

[b]HEAR- High Euricic Acid Rapeseed

[c]UoA- University of Arkansas

[d]IAES- Idaho Agricultural Experiment Station

[e]UoI- University of Idaho

[f]SDSU- South Dakota State University

[g]AAFC- Agriculture and Agri-Food Canada[h]NDSURF- North Dakota State University Research Foundation

[i]TTU- Texas Tech University.

Beeville

Spring rapeseed yielded highest with an overall mean of 2378 kg ha^{-1}, followed by flax with a mean yield of 1585 kg ha^{-1} (Tables 5 and 6). Camelina yielded lowest with a two- year average of 972 kg ha^{-1}. In 2007-2008, winter mustard produced no measurable seed yield. Safflower yields ranged from 524 kg ha^{-1} (PI 405985) to 1644 kg ha^{-1} (PI 544006) with an average yield of 1058 kg ha^{-1}. Flax yields ranged from 261 kg ha^{-1} (AC Lightning) to 934 kg ha^{-1} (MacBeth). In 2008-2009, the conditions were more favorable for plant growth and development. Camelina failed to produce measurable quantity of seed because of the poor competition with weeds and very limited herbicide weed management. In 2008-2009, spring rapeseed mean yield was 3924 kg ha^{-1}, while safflower and flax mean yield was 1579 kg ha^{-1} and 2611 kg ha^{-1}, respectively (Table 5). The crops were not harvested in 2010 due to poor stands.

Uvalde

At Uvalde, spring rapeseed yielded highest with an overall mean of 1010 kg ha^{-1}, followed by flax with a mean yield of 941 kg ha^{-1} (Tables 5 and 6). Winter mustard yielded lowest with one year genotype average of 149 kg ha^{-1}. Data was obtained only in 2009-2010.

Table 2. Experimental locations (South to North) and soil information for cool-season oil-seed crops in Texas during 2007-2010.

Location	*Average Elevation above sea level (m)*	*Latitude (North)*	*Longitude (West)*	*Soil classification*[a]
Weslaco	24	26°9′	97°59′	Sandy loam soil
Beeville	64	28°24′	97°45′	Parrita sandy loam
Uvalde	277	29°12′	99°47′	Uvalde silty clay loam
Beaumont	5	30°04′	94°07′	Bernard-Morey clayey silty loam
College Station	112	30°36′	96°18′	Ships clay
Prosper	208	33°14′	96°47′	Houston clay
Vernon	361	34°09′	99°17′	Silty clay loam
Lubbock	992	33°33′	101°53′	Acuff silty clay loam
Etter	1099	35°11′	101°50′	Sherm silty clay loam

[a]Soil Survey Staff, NRCS, USDA, 2011.

Table 3. Average monthly precipitation and minimum and maximum monthly average temperature distribution at experimental locations (South to North) in Texas during 2007-2010 (Wilson *et al*., 2007 and Yang *et al*., 2010).

Location	*Item*	*Month*											
		J	F	M	A	M	J	J	A	S	O	N	D
Weslaco	T_{max}[a]. (°C)	21	24	27	30	33	36	35	36	32	30	27	23
	T_{min}[b]. (°C)	9	12	14	18	22	25	25	25	17	16	14	10
	RF[c] (cm)	5	3	1	2	6	4	22	6	6	2	1	3
Beeville	T_{max}. (°C)	18	22	25	27	31	33	33	35	32	30	25	20
	T_{min}. (°C)	6	9	12	16	20	22	22	23	20	16	11	7
	RF (cm)	7	3	4	5	4	6	19	6	14	1	1	2
Uvalde	T_{max}. (°C)	14	17	23	25	28	31	31	34	31	26	14	17
	T_{min}. (°C)	0	1	7	11	17	21	22	22	18	8	0	0
	RF (cm)	8	4	12	8	7	10	14	8	8	1	8	5
Beaumont	T_{max}. (°C)	16	18	22	26	30	31	33	33	31	28	22	18
	T_{min}. (°C)	5	7	10	15	20	22	24	24	21	15	11	7
	RF (cm)	13	8	10	10	13	18	25	15	21	5	9	10
C. Station	T_{max}.(°C)	15	18	22	26	30	34	34	36	32	28	23	16
	T_{min}(°C)	2	4	8	12	18	22	23	23	19	12	8	3
	RF (cm)	10	3	8	7	9	7	13	7	11	10	7	6
Prosper	T_{max}. (°C)	13	15	22	25	29	34	35	37	32	26	21	15
	T_{min}. (°C)	0	2	7	11	17	22	23	23	19	11	8	1
	RF (cm)	8	6	14	11	17	12	10	7	12	17	9	6
Vernon	T_{max}. (°C)	12	14	21	24	28	34	35	37	31	26	21	12
	T_{min}. (°C)	-2	0	6	10	15	21	22	23	18	11	6	-1
	RF (cm)	3	3	4	7	9	13	6	4	9	5	1	2
Lubbock	T_{max}. (°C)	11	15	20	23	27	33	31	33	29	24	19	2
	T_{min}. (°C)	-4	-2	2	6	12	18	19	18	14	8	1	-3
	RF (cm)	2	2	5	3	8	8	9	5	5	3	0	1
Etter	T_{max}. (°C)	10	12	19	22	26	33	32	32	29	23	18	11
	T_{min}. (°C)	-7	-5	1	4	10	17	18	18	13	6	0	-5
	RF (cm)	1	1	4	5	5	10	5	10	8	4	2	1

[a]Tmax- Maximum monthly average temperature

[b]Tmin- Minimum monthly average temperature

[c] RF- Monthly average precipitation.

College Station

Flax yielded the highest with an overall mean of 1958 kg ha^{-1}, followed by safflower with a mean yield of 1400 kg ha^{-1} (Tables 5 and 6). Camelina yielded lowest with a three-year average of 612 kg ha^{-1}. Seed yield of winter rapeseed ranged from 1,531 kg ha^{-1} (White Pacific Gold) to 210 kg ha^{-1} (White Bionute) with a mean of 847 kg ha^{-1} for the cropping season 2007-2008. Spring rapeseed yielded in the range of 959 kg ha^{-1} (Gem) to 279 kg ha^{-1} (Sterling) with the mean yield of 727 kg ha^{-1}. However, there was no difference in yield when averaged across all genotypes between the spring and winter rapeseed. The seed yield of camelina ranged from 536 kg ha^{-1} (BSX-WG1) to 118 kg ha^{-1} (Cheyenne) with an average yield of 406 kg ha^{-1}.

Table 4. Analysis of Variance (ANOVA) of yields of tested cool-season crops in Texas during 2007-2010.

Source of Variation	*Degrees of Freedom*	*Mean Square*	*F- Value*[a]
rep(env)	24	42802.03	0.74^{NS}
cs	4	3227425.82	55.66***
env	11	3385979.35	58.39***
cs*env	34	771528.92	13.31***
Error	74	57984.85	-

env= environment; cs=crop species

*** Significant at P< 0.001

NS- Not significant at 0.05 probability level.

During 2008-2009, spring rapeseed yielded highest with an average seed yield of 2007 kg ha^{-1}, followed by flax with an average of 1671 kg ha^{-1}. Winter rapeseed yield ranged from 1154 kg ha^{-1} (Rally) to 2117 kg ha^{-1} (Rossini) with a mean yield of 1645 kg ha^{-1}. Safflower and winter rapeseed yielded comparatively high. Safflower yield ranged from 1490 kg ha^{-1} (PI-406002) to 926 kg ha^{-1} (PI-405988) with a mean yield of 1477 kg ha^{-1}. During the 2009-2010 cropping season, flax yielded higher compared to other cool-season crops with an average yield of 2092 kg ha^{-1}, followed by winter rapeseed with an average yield of 1604 kg ha^{-1}.

Table 5. Mean yields of flax, rapeseed, safflower, and camelina in individual years for all tested locations in Texas during 2007-2010.

		Weslaco				Beeville						
									Uvalde			
	2008	2009	2010	Mean	2008	2009	2010	Mean	2008	2009	2010	Mean
WR[a]	-	510 a	555 ab	533	-	2302ab	-	-	-	-	149 b	-
SR[b]	1676 a	982 a	1484 a	1381	832 a	3924 a	-	2378	-	-	1010 a	-
Flax	1670 a	369 a	949 ab	977	560 a	2611 ab	-	1585	-	-	-	-
Camelina	135 b	-	183 b	160	589 a	1354 b	-	972	-	-	-	-
Safflower	1352 a	1595 a	892 ab	1280	1058 a	1579 b	-	1369	-	-	941 a	-
		College Station				Prosper						
	2008	2009	2010	Mean	2008	2009	2010	Mean				
WR	847 ab	1645 a	1604 ab	1322	842 ab.	-	-	-				
SR	727 ab	2007 a	1232 ab	1366	324 b	-	-	-				
Flax	2109 a	1671 a	2092 a	1958	942 ab.	-	-	-				
Camelina	406 b	906 a	523 b	612	-	-	-	-				
Safflower	1369 a	1477 a	1353 ab	1400	2100 a.	-	-	-				
		Lubbock				Etter						
	2008	2009	2010	Mean	2008	2009	2010	Mean				
WR	-	-	-	-	565 a	-	-	-				
SR	480 a	1104 a	-	1253	-	-	-	-				
Flax	-	-	-	-	234 a	450 b	-	322				
Camelina	420 a	240 b	-	354	321 a	-	-	-				
Safflower	-	1158 a	996 a	1078	1045 a	1375 a	-	1210				

[a]WR= Winter Rapeseed

[b]SR= Spring Rapeseed

Note: Yields were compared among different species within a year and within a location.

Prosper

Two out of three years (2008-2009 and 2009-2010), cool-season crops failed to produce significant amounts of seed yield. Safflower yielded highest with an overall mean of 2100 kg ha^{-1}, followed by flax with a mean yield of 942 kg ha^{-1} (Tables 5 and 6). However, mean data represented only one year, 2007-2008. During 2007-2008, safflower yielded highest with a mean seed yield of 2100 kg ha^{-1} and a maximum yield of 2218 kg ha^{-1} (PI 544006). Flax and winter rapeseed mean yields were 942 kg ha^{-1} and 842 kg ha^{-1}, respectively. Camelina and spring rapeseed yields were poor in Prosper during 2007-2008. For winter rapeseed, the cultivars White Bionute and White Idagold failed to produce harvestable seed.

Table 6. Mean yield of flax, rapeseed, safflower, and camelina by location in Texas during 2007-2010.

Location/species	*Spring Rapeseed*	*Winter Rapeseed*	*Flax*	*Camelina*	*Safflower*
Weslaco [c]	1381a	533 ab	977 ab	160 b	1280 a
Beeville [b]	2378 a	1432 a	1585 a	972 a	1319 a
Uvalde [a]	1010	149	676	415	941
College station [c]	1366 a	1322 a	1958 a	612 b	1400 a
Prosper [a]	842	324	942	.	2100
Lubbock [d]	1253 a	.	.	354 a	1078 a
Etter [d]	.	565	322	322	1210
State Average	1372	720	1075	473	1240

[a] represents one year of data

[b] represents two years of data

[c] represents three years of data

[d] represents mixed years data

. = no data;

Note: The means were assigned letters for a particular location if there were at least two years' of data; if there is only one year data, mean yield of genotypes were reported.

Lubbock

Spring rapeseed yielded highest with an overall mean of 1253 kg ha^{-1}, followed by safflower with a mean yield of 1078 kg ha^{-1} (Tables 5 and 6). Fall-sowed winter rapeseed and spring sowed flax produced no yield at this location. In 2008, the spring rapeseed produced 480 kg ha^{-1}. In 2009, safflower yielded highest with 1158 kg ha^{-1}, followed by spring rapeseed with 1104 kg ha^{-1}. In 2010, the safflower produced 996 kg ha^{-1}, while all other crops failed to produce any yields in 2010.

Etter

Safflower yielded highest with an overall mean of 1210 kg ha^{-1}, followed by winter mustard with a mean yield of 565 kg ha^{-1} (Tables 5 and 6). Camelina yielded lowest with a three year average of 322 kg ha^{-1}. In Etter, all winter crops of 2007 and spring crops of 2008 were largely affected by damage caused by rabbits. In the spring of 2008, poor stands contributed to the decreased yields of all cool-season crops. Spring and winter rapeseed failed to produce any yields in 2009-2010 due to severe winter injury. Safflower produced higher yields compared to other cool-season crops in both 2008-2009 and 2009-2010 with a mean yield of 1045 and 1375 kg ha^{-1}, respectively.

Yields of evaluated crop species

Rapeseed

Generally, spring rapeseed seemed to be well adapted to most of the sub-tropical climates (College Station, Weslaco, and Beeville) of Texas with the state average of 1372 kg ha^{-1} (Table 6). Spring rapeseed recorded the highest yield (2378 kg ha^{-1}) in Beeville. College Station and Weslaco locations produced reasonable yields of spring rapeseed averaged across three site-years due to good emergence and favorable environmental conditions like precipitation and less insect and disease pressure. The spring rapeseed yield potential appeared to be limited in Amarillo and Vernon because of the late-spring heat conditions that prevailed during the reproductive stages of the plant development. Spring planted cool-season crops did not have sufficient time to develop adequate biomass prior to the on-set of high temperatures. Additionally, flowering occurred during high heat stress periods, which may negatively impact pollination and seed development. However, the spring rapeseed yielded well in Lubbock/Pecos (1253 kg ha^{-1}). The emergence and stand establishment of all winter type cool-season crops were largely affected by frost injury in most of the north locations (Amarillo, Lubbock, Vernon, and Prosper) where susceptible growth stages (<4 leaf) coincided with the freezing temperatures. For most of the spring season-cool crops, the planting dates were delayed until March in the north to avoid the damage due to the freezing injury. Winter rapeseed yielded highest in Beeville and College Station because of the mild temperatures and minimal winter-kill. The spring rapeseed yielded comparatively higher than the winter rapeseed in almost of the tested locations due to less abiotic stress due to cold injury.

Table 7. Mean oil content of flax, rapeseed, safflower, and camelina evaluated in Texas during 2007-2010.

Crop	*Oil %(w/w)[a]*
Flax	38.3 a
Winter Rapeseed	36.2 a
Spring Rapeseed	34.5 ab
Camelina	28.2 b
Safflower	21.4 c

[a]Mean oil content of each species was calculated by combining three years data.

Flax

Flax had wide range of adaptability to the diverse environments south and central Texas; however, not so much in northern locations of Amarillo, Lubbock, and Vernon This is probably due to the Mediterranean and Southwest Asian origin (Millam *et al.*, 2005). Flax yield ranged from 1671 to 2109 kg ha^{-1} with a three-year average of 1958 kg ha^{-1} in College Station, where the yield-limiting stresses like cold injury, heat stress, and pests and diseases were minimal. Flax yielded more than 2000 kg ha^{-1} in two out of three years in College Station. Beeville produced the second highest yield for flax with a two-year average of 1585 kg ha^{-1}, where the drought conditions were predominant. Flax yielded relatively high in South Texas locations and supported the fact that flax acreage was mostly concentrated on the Coastal Bend of Texas in 1900's due to high level of adaptation. Flax yields were poor in most of the North Texas locations due to adverse cold and heat temperatures during crop growth and development stages. The level of flax yield potential in the state is comparable to the state average yield of North Dakota (1232 kg ha^{-1}) (USDA-NASS, 2011). However, lower temperatures during stand establishment stage and high temperature stress at critical reproductive stages in the Northern locations of Texas lowered the state flax yields significantly. Flax trials conducted along the Coastal Bend of Texas in 1960-1970 reported a maximum yield of 1120 kg ha^{-1}(Hodges *et al.*, 1970), which was much lower than the maximum yield of current trials (1958 kg ha^{-1}). Yield improvement of flax from 1930 to now has been nearly double, mainly due to improved varieties and agronomic practices.

Camelina

Camelina produced less than 500 kg ha^{-1} in most of the locations, except in College Station and Beeville. The major problem encountered and that contributed to lower yields of camelina was poor stand establishment due to small seed size. The yield potential of camelina in Texas was generally lower than the yields of other camelina producing states like Minnesota (Putnam *et al.*, 1993) and Montana (McVay and Lamb, 2008).

Safflower

Safflower produced decent yields in diverse environments of Texas (state yield average of 1240 kg ha^{-1}) because of its relative tolerance to drought conditions (Kephart, *et al.*, 1990). Safflower produced higher yields in College Station with a yield range of 1353 to 1477 kg ha^{-1} and three-year mean yield of 1400 kg ha^{-1} due to minimal yield-limiting factors such as pests, and diseases. At Weslaco, safflower yields ranged from 892 to 1352 kg ha^{-1} with a three-year average of 1280 kg ha^{-1}. At Beeville, safflower yields ranged from 1058 to 1579 kg ha^{-1} with a two-year average of 1369 kg ha^{-1}. At Etter, safflower yields ranged from 1045 to 1375 kg ha^{-1} with a two-year average of 1210 kg ha^{-1}. Safflower yielded more than 1200 kg ha^{-1} in 4 out of 9 locations. However, the state average yield for safflower in Texas was about 250 kg ha^{-1} lower than the national safflower average (USDA-NASS, 2011).

Safflower has a broad range of adaptability to the diverse environments of Texas as it produced relatively high yields in most of the regions of Texas. The average yield for Texas in three tested years was 1240 kg ha^{-1}. However, lower oil concentration may limit its biofuel potential in Texas and the nation. The careful selection of safflower improved varieties by North Dakota State University suggested a maximum oil concentration of 44% is possible (Berglund *et al.*, 2007). Cultivars with higher oil concentration coupled with selection for improved yield potential could make safflower a possible cool-season oilseed crop for Texas.

Oil concentration

Due to missing data in many of the locations and lack of measurable seed for analyzing the oil concentration, the data was combined across years and all locations to obtain the mean oil concentration for each individual crop species (Table 7). The oil concentration (w/w) was highest in flax (38.3%) followed by winter rapeseed (36.2%). However, there was no difference between the oil concentrations of flax and winter rapeseed ($p<0.05$). The large error variance produced in combining the locations might have masked the real difference between the oil concentration of the different species. If the total oil concentration was estimated on a land area basis, based on the average state yields of Texas, spring rapeseed yielded about 477 L ha^{-1}, flax yielded 412 L ha^{-1} , and safflower yielded about 271 L ha^{-1} of oil . If the maximum yield potential for each species in Texas was considered, spring rapeseed yielded about 832 L ha^{-1} and flax yielded 758 L ha^{-1}. Even though safflower produced decent oil-seed yields in most of the locations, the lower oil concentration of safflower (Table 7) limits the biofuel potential of safflower.

Conclusions

Spring rapeseed was the most prominent crop species adapted to the diverse environments of Texas. Flax has potential for biofuel feedstock production in specific regions of Texas. Flax was well adapted to south and central Texas with the highest state average oil concentration of 38% on weight basis. However, the adaptability of flax in North Texas was limited due to the high heat and cold stresses. With enhanced oil concentration, safflower could be a potential candidate crop for biofuel feedstock production in Texas. The main problem encountered in the camelina production in the majority of Texas locations was poor stand establishment due to small seed size. With the improved site-specific management practices and genetics, growing the appropriate crop species suitable to its environment is essential to maximize the biofuel feedstock production in Texas.

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