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Compression ignition engine performance and emission evaluation of industrial oilseed biofuel feedstocks camelina, carinata, and pennycress across three fuel pathways

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HIGHLIGHTS

- Performance of camelina, carinata, and pennycress based biofuels was similar to conventional feedstocks.
- Triglyceride blends may be an ideal fuel pathway for farm-scale fuel production.
- Biodiesel offers several emission benefits over other biofuels.
- Renewable diesel had similar engine performance to petroleum.

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ABSTRACT

Industrial oilseeds camelina (*Camelina sativa* L.), carinata (*Brassica carinata*), and pennycress (*Thlaspi arvense* L.) offer great potential as biofuel feedstocks due to their non-food nature and positive agronomic attributes. This research focused on compression ignition (CI) engine performance and emissions of these industrial oilseeds as compared to both traditional feedstocks and petroleum diesel. A John Deere 4.5 L test engine was used to evaluate these oils using three fuel pathways (triglyceride blends, biodiesel, and renewable diesel). This engine research represents the first direct comparison of these new biofuel feedstocks to each other and to conventional sources. For some industrial oilseed feedstock and fuel pathway combinations, this study also represents the first engine performance data available. The results were promising, with camelina, carinata, and pennycress engine performance very similar to the traditional oils for each fuel pathway. Fuel consumption, thermal efficiency, and emissions were all were typical as compared to traditional oilseed feedstocks. Average brake specific fuel consumption (bsfc) for the industrial oilseed biofuels was within ±1.3% of the conventional oilseed biofuels for each fuel type. Initial research with triglyceride blends (TGB), formed by blending straight vegetable oil with gasoline, indicate it may be an ideal fuel pathway for farm-scale fuel production, and was compatible with a direct injection CI engine without modification. TGB had lower fuel consumption and a higher thermal efficiency than biodiesel for each feedstock tested. For several categories, TGB performed similar to petroleum diesel. TGB volumetric bsfc was only 1.9% higher than the petroleum runs. TGB combustion characteristics were similar to biodiesel. Biodiesel runs had several emission benefits such as reductions in carbon monoxide (CO), non-methane hydrocarbons (NMHC), volatile organic compounds (VOCs), and formaldehyde (CH_20) emissions as compared to TGB runs. The renewable diesels had petroleum-like engine performance and combustion characteristics, while still maintaining some of the benefits of biodiesel such as reduced CO emissions. Nitrogen oxides (NOx) emissions were also 6% lower for renewable diesel runs than petroleum. Both crude and refined oil was used as feedstock, and did not significantly affect engine performance or emissions in a modern CI engine.

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1. Introduction

1.1. Need for biofuels and economical feedstocks

As the world's use, demand, and cost of energy in terms of economic and environmental impact steadily increase, the need for renewable fuels is greater than ever. The U.S. transportation sector's mandated use of biofuels attempts to alleviate these energy impacts [1]. The U.S. military has also turned to biofuels as an important alternative to petroleum fuel. The purchase of fuel from foreign markets for military operations has been identified by senior military leadership as a key vulnerability [2]. All military branches have recently set use goals of alternative fuels that are cost competitive, domestically produced, and have a lifecycle greenhouse gas footprint equal to or less than petroleum. Additionally, Department of Defense (DOD) officials have said that any alternative fuels for DOD operational use must be derived from a non-food crop feedstock [3].

Like the larger scale U.S. transportation sector and military users, fuel is very important to the agriculture community. Farm use of distillate fuel oil is significant, especially in the agricultural centers of the U.S. and other parts of the world. For example, farm use represents more than 20% of total fuel consumption in Iowa [4]. The prices paid by farmers for fuel and other energy-based inputs nearly tripled from 2002 to 2005, and continues to steadily increase [5,6]. The United States Department of Agriculture (USDA) found higher energy-related production costs would generally lower agricultural output, raise prices of agricultural products, and reduce farm income [7]. In response to these increased fuel input costs, several farmers have decided to grow and produce their own biofuels on the farm. This gives them greater control over one of their largest input costs. Farm-scale fuel production allows a farmer to avoid retail margins and transportation costs of both the crop and fuel. It also has several collateral benefits, such as the ability to control the quality of their fuel and gives them protection from fuel shortages at critical times like planting and harvest [8–11].

Despite the need for these biofuels, a few issues hinder future growth. One major issue is the high cost of traditional biofuel feedstock. Feedstock cost represents 75–80% of the cost to make biodiesel [12–14]. As shown in Fig. 1, recent grain commodity costs in soybeans and other conventional feedstocks have been historically high and are driving this limitation. Another issue is that land use requirements of conventional feedstocks are too great to offset a significant portion of petroleum use. A recent study estimated that only 6% of petroleum diesel demand would be satisfied if all U.S. soybean production were dedicated to biodiesel [16]. Finally, many traditional biofuel feedstocks also have food uses, creating a "food versus fuel" debate. With grains making up 80% of the world's food supply, some view food and fuel as competing interests, and are concerned biofuels drive up the cost of food [17,18].

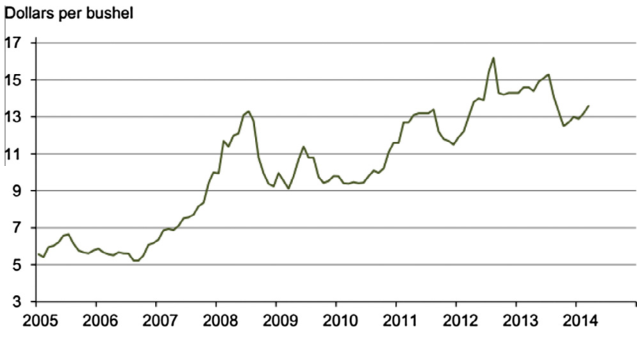

Fig. 1. U.S. prices received for soybeans [15].

1.2. Industrial oilseeds

Industrial oilseeds are alternative low-cost oilseeds which have great potential to increase biofuel use by alleviating the problems outlined above. Due to their non-food nature, they steer clear of any food versus fuel debates. In addition to their high oil yield and quality, industrial oilseeds have several agronomic advantages over conventional oilseeds such as a short growing season, cold weather tolerance, ability to thrive on marginal lands (salinity, fertility), and low input requirements (water, pesticide, fertilizer). These advantages can equate to lower oil production costs [18–28].

The industrial oilseeds of primary focus for this research were camelina (*Camelina sativa* L.), carinata (*Brassica carinata*), and pennycress (*Thlaspi arvense* L.). These oilseeds were selected for their ability to grow well in much of the U.S., their compatibility with existing agriculture and fuel infrastructure, and potential to see widespread adoption in the near term. Several traditional oils used for biofuels were also included in the research: soybean, canola, sunflower, and corn. These traditional options were included, not only as a performance baseline, but also because this research included previously unexplored fuel pathways.

The positive agronomic attributes of the industrial oilseeds camelina, carinata, and pennycress make them compatible with off-season cropping, fallow cropping, relay cropping, or other non-traditional cropping systems. These cropping methods allow for the production of industrial oilseeds without competition with other major cash crops, and can increase biofuel feedstock production on existing farm lands at low input costs. Not competing with conventional cash crops not only helps keep the cost of production low, it may help the popularity of these oilseeds spread.

A few examples of these cropping systems follow, although plant scientists worldwide are exploring several other options for these oilseeds than described here. Camelina is being grown during a normally fallow portion of a winter wheat rotation in the Western U.S. and Canada, with an estimated renewable fuel yield potential of an additional 100 million gallons per year (MGY) without an increase is total agricultural acres [29]. Carinata is being explored as an off-season crop to soybeans, peanuts and cotton in the Southern U.S. Yield estimates from this cropping system in Florida alone are 40–100 MGY [30]. Pennycress is being explored in the Midwestern U.S. as an off-season crop between a corn-soybean rotation. Yield potential for this rotation is 4 BGY, which would be a significant increase over current U.S. total biodiesel production [31].

The U.S. military has expressed interest in these industrial oilseed feedstocks, and began flight trials with camelina based jet fuel in 2010 and carinata based jet fuel in 2012 [32,33]. The United State Air Force (USAF) Chief Scientist recently identified the use of efficient and abundant non-food source biofuels would be a game changing technology in energy generation for 2011–2026 [34]. Despite the desire for this new class of oilseeds, the industry's crushing, fuel processing, and distribution infrastructure all need to mature. Senior DOD leaders have called this the classic "chicken and egg" scenario. Defense Production Act Title III Programs have been established focusing on the creation of an economically viable production capacity for advanced drop-in biofuels [35]. Even with these programs, currently most U.S. farmers that would want to grow camelina, carinata, or pennycress would not be able to market the crop locally. Using the crop to produce on-farm fuel gives a grower a local market for these crops until a commercial market matures.

1.3. Fuel pathways for vegetable oil

Vegetable oil can be converted to a biofuel for use in CI engines through several fuel pathways. Using straight vegetable oil (SVO) directly as a diesel fuel substitute is one of the oldest biofuels [36]. SVO as a diesel fuel substitute has been well studied. Several studies have found SVO engine durability issues during long term use. Carbon deposits in the combustion chamber and lubricating oil thickening are problems observed during testing [37]. SVO and petroleum diesel mixtures have also been researched for several feedstocks and volumetric ratios. While recommendations on using SVO as a diesel fuel extender have been mixed, several studies have also shown unfavorable results [38–46]. Due to the documented reduction in engine durability during long term use in unmodified engines, SVO and SVO + petroleum diesel blends were not used in this engine performance study.

One of the main concerns with using SVO directly as a fuel in CI engines is that several fuel properties, especially viscosity, vary considerably from petroleum diesel. One way researchers have addressed this is by blending SVO with various thinning agents other than petroleum diesel such as ethanol, methanol, 1-butanol, other solvents, or a combination thereof. In some cases, the blending agent is normally immiscible with SVO and a surfactant is required. There are other names and variations in the literature for this type of blend including hybrid fuels, cosolvents, emulsions, and others [47–50]. In addition to the reduction in viscosity, research indicates other potential combustion, fuel property, and emission benefits for some blend types [37,47,51].

A triglyceride-blend (TGB), is a variation of this blending/dilution method, formed when SVO is mixed with another less viscous fuel (other than petroleum diesel), and the resulting solution used as a petroleum diesel substitute. E10 gasoline was used to form the TGBs in this study. TGB is a naming convention/abbreviation used at Colorado State University (CSU) for this type of biofuel, and will be used throughout this report. Peer reviewed literature found on this type of blend is extremely limited, although several U.S. farmers have been successfully using SVO-gasoline blends for several years [52]. Using gasoline as a blending agent has several benefits: it is readily available, has high energy content, inexpensive, and is completely miscible and stable with SVO. Like other blends of this nature, as compared to biodiesel, producing TGBs are fast, have low energy inputs, do not create waste products, and do not require a catalyst [50]. TGBs change the physical properties of SVO to be more similar to petroleum diesel so they can be used directly in unmodified engines. This research investigates the feasibility of TGBs as a suitable on-farm fuel, and compares engine performance to petroleum diesel and other biofuels.

Biodiesel was also used as fuel pathway during this evaluation. Conversion of triglycerides to esters (biodiesel) also changes fuel properties to be more similar to petroleum diesel. Biodiesel from conventional feedstocks has been well studied, but engine performance testing using industrial oilseeds camelina, carinata, and pennycress as a biodiesel feedstock is limited. Most research has focused on biodiesel conversion and quantification studies [26,31,53], with some CI engine performance data studies using camelina SVO [31].

Recently, another alternative method to convert triglycerides to fuel known as renewable diesel holds great promise as a renewable drop-in alternative to petroleum. The U.S. military has already identified this fuel pathway as most compatible with military operations [3]. CI engine testing using these industrial oilseeds as a renewable diesel feedstock is also limited.

The main objectives of this research project were to conduct compression ignition engine performance testing and emissions evaluation using industrial oilseeds (camelina, carinata, and pennycress) and conventional oilseeds feedstocks (soybean, canola, sunflower, and corn) comparing multiple fuel pathways. The research explores if using industrial oilseeds have any engine performance differences as compared to conventional biofuel feedstocks. The research also investigates how underexplored fuel pathways like TGB and renewable diesel compare to petroleum and biodiesel.

2. Experimental setup

2.1. Test fuel preparation

All testing was performed at the Engines and Energy Conversion Laboratory (EECL) at CSU. The vegetable oils used in this evaluation were obtained from various sources; most oils were mechanically extracted via screw or expeller oilseed presses and lightly filtered. The sources of oil and other testing materials is shown in Table 1. Oil extraction and fuel preparation methodology was kept consistent with typical farm-scale fuel procedures. Since most farm-scale producers do not have access to large scale refining, crude oil was used as the biofuel feedstock unless otherwise noted. To evaluate oil feedstock refinement's effect on engine performance and emissions, biofuels produced from both crude and refined, bleached, and deodorized (RBD) soybean and corn oil were used in testing. Since vegetable oil quality and properties can vary with season, location, and other factors, the same batch of oil was used to produce each type of biofuel.

The TGBs used in the evaluation were formed by filtering SVO with a 10 μm polypropylene filter, then blending the SVO with E10 at a 3:1 volumetric ratio. The resulting TGB was vigorously agitated in a high-density polyethylene (HDPE) container before filtering again to 1 μm.

SVO was converted to biodiesel in via transesterification (alcoholysis) in a research-scale reactor in the EECL. Crude vegetable oil was added to the reactor, recirculated, and heated to 60 °C. In a separate container, methoxide was prepared from methanol and potassium hydroxide (KOH) at a 1:5 M ratio and 1 wt% KOH. After adding the methoxide to the oil, the mixture was recirculated for two hours to help the conversion to fatty acid methyl esters. Following the reaction and settling, the lower glycerol layer was separated. The biodiesel was then water washed until a neutral pH was obtained, air dried, and filtered to 1 μm before engine testing.

Applied Research Associates (ARA) and Chevron Corporation created the renewable diesels in this evaluation. ARA provided two variations of their Renewable, Aromatic, Drop-in Diesel (ReadiDiesel™) produced through their Catalytic Hydrothermolysis (CH) process. One ARA described as "heavy" and is intended to meet the Navy Distillate Diesel Fuel specification (NATO symbol F-76). The other was described as their "full boiling range" fuel, and is intended as a drop-in, #2 petroleum diesel substitute. Both were created using carinata oil as feedstock. Chevron labeled their renewable diesel as "experimental hydrotreated renewable diesel", and was created from camelina oil. Hydrotreating of vegetable oils and the Catalytic Hydrothermolysis (CH) process is described in other publications [55].

2.2. Test engine setup

Engine performance and emission assessments were conducted using a 4-cylinder, 16 valve, turbocharged and intercooled, 4.5 l, 175 hp, John Deere 4045 PowerTech Plus test engine. The test engine, shown in Fig. 2, is configured with a variable geometry turbocharger (VGT), exhaust gas recirculation (EGR), and electronically controlled high-pressure common rail (HPCR) fuel injection and meets Tier 3/Stage IIIA emissions specifications. The test engine is connected to an eddy current dynamometer (Midwest Inductor Dynamometer 1014A). The dynamometer and dynamometer controller (Dynesystems Dyn-LocIV) were used to load the engine and maintain a constant engine speed and load for each test fuel. The engine's standard fuel tank is filled with dyed off-road

Table 1
Source of testing materials.

Material	Source	Location
Carinata oil	Agrisoma Bioscience, Inc.	Saskatoon, SK, Canada
Camelina oil	ClearSkies, Inc.	Bozeman, MT, USA
Pennycress oil	Arvens Technology, Inc.	Peoria, IL, USA
Soybean oil	South Dakota Soybean Processors, LLC	Volga, SD, USA
Corn oil	Glacial Lakes Energy	Watertown, SD, USA
Canola oil	Painted Rock Farms	Stratton, CO, USA
Sunlower oil	Prairie View Farms	Penokee, KS, USA
Carinata R100	Applied Research Associates, Inc.	Panama City, FL, USA
Camelina R100	Chevron Corporation	Richmond, CA, USA
Methanol, 99.85 wt.% purity	Industrial Chemicals Corporation	Arvada, CO, USA
Potasium hydroxide, ACS Grade	Avantor Performance Materials, Inc.	Center Valley, PA, USA
Diesel Fuel, Grade No. 2-D S15	Team Petroleum, LLC	Fort Collins, CO, USA
E10 Gasoline, ethanol% certified	Agfinity Cooperative	Eaton, CO, USA
Polypropylene Filter Bags	Duda Energy LLC	Decatur, AL, USA

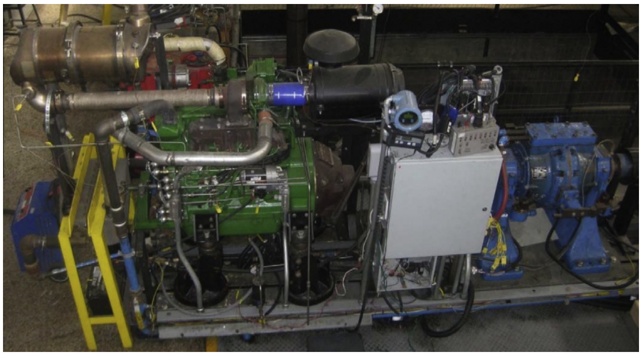

Fig. 2. 4.5 L 175 HP John Deere 4045 at the EECL.

petroleum diesel used for engine warm-up and cool-down, and to flush the engine between test fuel runs. A three way solenoid valve and lift pump is used to deliver test fuels from an auxiliary fuel tank. Fuel flow is measured by a coriolis meter (Micro Motion 2700R11BBCEZZZ) and verified gravimetrically by a precision balance (Mettler-Toledo MS32000L). A Kistler Instrument Corporation PiezoStar® pressure sensor (6056A41) with glow plug adaptor (6542Q128) was installed in the glow plug port of cylinder 1 to record in-cylinder pressure data. A custom system designed in the EECL uses a National Instruments PXI-1002 connected to Kistler Type 5010 charge amplifiers to record high speed combustion data from the in-cylinder pressure. An incremental encoder is connected to the crankshaft on the engine to provide crankshaft position as well as instantaneous engine RPM. Pressure and temperature values for several engine locations can be independently controlled and values logged via National Instrument's data acquisition hardware (DAQ) and LabVIEW virtual instrument (VI) software. Engine control unit (ECU) data was also recorded.

2.3. Exhaust gas sampling and emissions measurement

The test engine exhaust stream is sampled by two different probes. One averaging probe extracts exhaust for gaseous emissions measurement. Criteria pollutant measurements were made using a Rosemount 5-gas emissions analysis system that includes chemiluminescence measurement of nitric oxide (NO), nitrogen dioxide (NO_2) and total oxides of nitrogen (NOx) (Siemens NOx-MAT 600), flame ionization detection (FID) of total hydrocarbons (THC) (Siemens FIDAMAT 6 Total Hydrocarbon Analyzer), paramagnetic detection of oxygen (O_2) (Rosemount NGA 2000 PMD), and non-dispersive infrared (NDIR) detection of carbon monoxide (CO) and carbon dioxide (CO_2) (Siemens ULTRAMAT 6). In addition to the 5-gas emissions analysis system, a Fourier Transform Infrared (FTIR) spectrometer (Thermo Fisher Scientific Nicolet 6700) was used to obtain speciated measurement of hydrocarbons through C4, and a variety of hazardous air pollutants and volatile organic compounds (VOCs) such as formaldehyde, acetaldehyde, and acrolein.

2.4. Particulate matter sampling and measurement

The second exhaust probe samples a small portion of the exhaust stream for particulate measurements. All of the PM measurements were taken after the exhaust sample is diluted with clean air in a mini dilution tunnel. The dilution air was first cleaned by a high-efficiency particulate absorption (HEPA) filter and then filtered by an activated charcoal filter. A turbine flow meter was used to measure the flow rate of clean dilution air. A valve located downstream of the turbine flow meter was used to control the dilution ratio. The mixture is passed through a residence chamber to simulate particulate mixing with ambient air. Then a portion of the flow is pulled from the base of the residence chamber through a PM10 cyclone, which eliminates particulates larger than 10 μm. The remaining particulates (PM_{10}) is collected on 46.2 mm Teflon filters (Whatman PLC 7592-104) filter downstream cyclone. The Teflon filters are weighed before and after the test using a microbalance (Mettler-Toledo MX5) with a precision of 1 μg.

A second cyclone, also at the base of the residence chamber, is used to collect PM onto 46.2 mm quartz filters (Whatman PLC 1851-047). The quartz filters were subsequently analyzed using a Sunset Labs OC/EC Analyzer to determine elemental carbon (EC) and organic carbon (OC) ratios. Finally, a Grimm Technologies Sequential Mobility Particle Sizer (SMPS) was also connected to the dilution tunnel. The SMPS was used to measure particle size distributions from 10 to 1000 nm (nm). The basic engine test schematic is shown in Fig. 3 and the mini dilution tunnel schematic is shown in Fig. 4.

2.5. Testing procedure, operating conditions, and fuel properties

Engine performance and emissions data was recorded at 50% load and intermediate speed setpoints (250 N-m and 1700 rpm), which corresponds to mode 7 of ISO 8178 Non-Road Steady Cycle (NRSC) [56]. After switching to test fuel, fuel flow was adjusted to hold desired load, and the engine was allowed to stabilize. Once steady state was achieved, data was collected for 5-min intervals. Between each run, the engine was operated on petroleum diesel to purge the system of test fuel. Petroleum diesel data was recorded at the beginning, middle, and end of the evaluation. Seven feedstocks were evaluated, using three fuel pathways, and for two

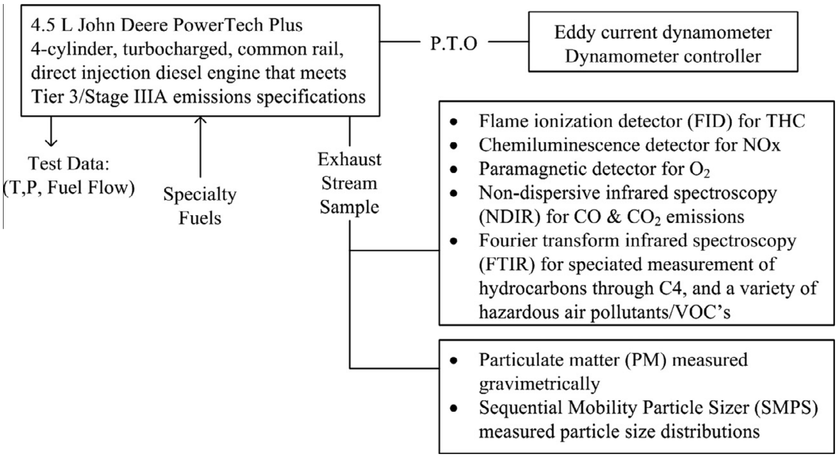

Fig. 3. Basic schematic of engine performance test setup.

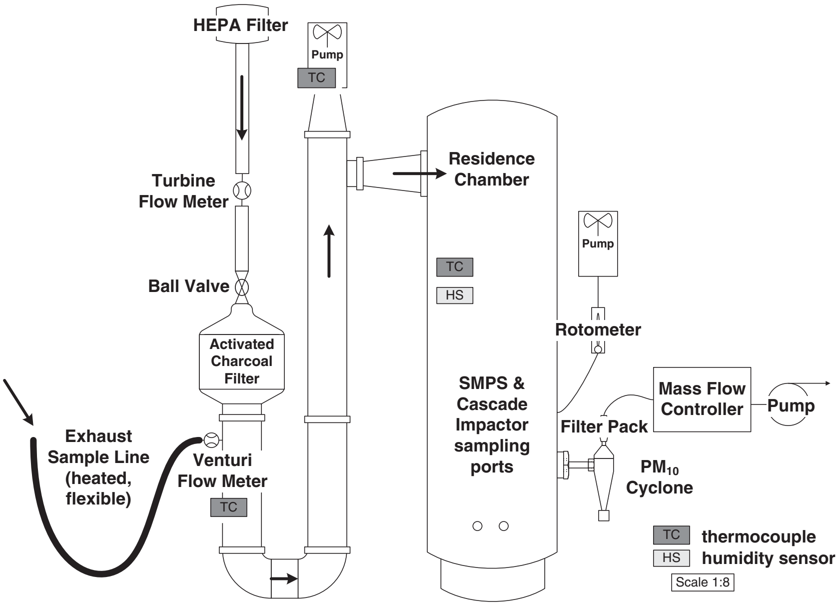

Fig. 4. Schematic of mini dilution tunnel at EECL [54].

refinement levels as shown in Table 2. Not every combination was available due to feedstock availability. Engine operating conditions during the testing period are shown in Table 3. Several physical properties of the test fuels were measured in the Advanced Biofuel Combustion and Characterization Laboratory (ABC^2) in the EECL. These fuel properties, and the instrument used to measure them, are shown in Table 4.

3. Results and discussion

3.1. Brake specific fuel consumption results

Brake specific fuel consumption is a frequently used metric to describe engine efficiency. A low value for bsfc is desirable since at a given power level less fuel will be consumed. Fig. 5 shows the bsfc for all fuels used in the evaluation grouped by fuel type. Error bars indicate the standard deviation in each run. For the petroleum diesel runs, the graph indicates the median value of the three petroleum runs. The three diesel runs had nearly identical bsfc results, indicating low variability throughout the testing period and a valid comparison of feedstocks and fuel types.

The industrial oilseed derived fuels have very similar performance as compared to the traditional oilseeds. Average bsfc for the industrial oilseed biofuels was within ±1.3% of the conventional oilseed biofuels for each fuel pathway. Refinement level did not have a significant effect on bsfc. Only minor differences were observed between the crude and RBD runs for the two feedstocks tested.

Fuel pathway did have an effect on bsfc. The biodiesel run had a higher bsfc than the TGB run for every feedstock. The average bsfc for all biodiesel runs was 246.9 g/kW-hr while the average for TGB runs was 239.1 g/kW-hr, a 3.2% reduction. The renewable diesels had lower bsfc values than the other biofuel types, with results very similar to the petroleum runs. The three run average for the R100 biofuels was 219.2 g/kW-hr and the three run average for petroleum diesel was 222.7 g/kW-hr. The bsfc results are related to the energy content differences of the test fuels shown in Table 4.

The bsfc results described above were for fuel flow measured on a mass flow basis. In practice, operators typically measure engine efficiency and fuel economy (fuel flow) on a volumetric basis – miles per gallon or gallons per hour. When taking in account the density differences of the fuel types, the biofuels generally had

Table 2
Engine performance test runs.

Run #	Fuel type	Feedstock type	Refinement level
1	DIESEL	*Petroleum*	
2	B100	Carinata	Crude
3	TGB		
4	$R100_1$		
5	$R100_2$		
6	B100	Camelina	Crude
7	TGB		
8	R100		
9	B100	Pennycress	Crude
10	TGB		
11	DIESEL	*Petroleum*	
12	B100	Soybean	Crude
13	B100		RBD
14	TGB		Crude
15	TGB		RBD
16	B100	Corn	RBD
17	TGB		RBD
18	TGB		Crude
19	B100	Canola	Crude
20	TGB		
21	B100	Sunflower	Crude
22	TGB		
23	DIESEL	*Petroleum*	

Notes:
B100 = 100% biodiesel
R100 = 100% renewable diesel
TGB = triglyceride blend (75% oil + 25% gasoline by volume)
RBD = refined, bleached, deodorized

Subscripts:
1 = heavy blend
2 = full boiling range

Table 3
Engine operating conditions during testing period.

Engine parameter	Mean	Coefficient of variance %	Engine parameter	Mean	Coefficient of variance %
Torque (N-m)	251	0.4	Jacketwater In Temp (C)	67.2	1.3
Power (kW)	44.8	0.5	Jacketwater Out Temp (C)	69.9	1.1
Speed (RPM)	1700	0.0	Engine Oil Temp (C)	90.6	0.2
BMEP (kPA)	703	0.0	Fuel Inlet Temp (C)	22.3	0.7
Fuel Supply Flow (g/min)	177	3.7	Fresh Air Temperature (C)	23.8	0.3
Throttle Position (%)	54.3	0.0	Inlet Air Temp (C)	35.1	1.0
Turbo Speed (RPM x 1000)	82.7	0.3	Manifold Air Temperature (C)	27.5	0.3
Start of Injection (°BTDC)	2.60	3.5	Compressor Inlet Air Temperature (C)	31.4	3.3
Intake Manifold Pressure (psig)	5.98	4.2	Charge Air Pre-IC Temp (C)	94.4	0.3
Exhaust Manifold Pressure (psig)	7.42	1.5	Charge Air Post-IC Temp (C)	22.2	0.5
Engine Oil Pressure (psig)	45.6	5.0	IC Water Inlet Temp (C)	12.9	0.1
Precooler Pressure (psig)	6.47	1.3	IC Water Outlet Temp (C)	15.6	0.2
Pre DPF Pressure (psig)	0.160	33.1	Pre DPF Temp (C)	350	0.2
Rail Pressure (psig)	17900	0.2	Post DPF Temp (C)	311	0.2

performance closer to that of petroleum diesel than on a mass flow basis, due to their higher density. Several TGBs have a volumetric bsfc only slightly higher than diesel fuel, with the mean value for all TGBs only 1.9% higher than the petroleum runs.

3.2. Brake thermal efficiency results

Brake thermal efficiency can be used to compare two engines if using the same fuel, or compare efficiency of an engine using multiple fuels. In general terms, thermal efficiency is how efficient an engine can convert the energy in the fuel into useful power. As shown in Fig. 6, all biofuels had higher thermal efficiencies than petroleum diesel. Error bars indicate the standard deviation in each run. For the petroleum diesel runs, the graph indicates the median value of the three petroleum runs. The TGBs had a higher thermal efficiency than the B100 fuels for all seven feedstocks, with an average thermal efficiency 2% higher than petroleum. Other researchers have found biodiesel thermal efficiency similar to petroleum, or in some cases higher than petroleum especially at lower speeds [57]. The increased lubricity of the biofuels could cause a reduction in engine friction and improved efficiency at this load [57]. For the TGB fuels, the improvements in efficiency could also be tied to the improved spray patterns in combustion due to explosive vaporization of the low boiling constituents [37]. Additionally, since the heating value of the biofuels is lower, more mass needs to be injected into the combustion chamber. At low load this may be realized as improved jet penetration and air utilization.

3.3. Brake specific emission results

Brake specific emissions (BSE) relate emission mass flow to engine loading. BSE takes into account different power levels and fuel composition. Biofuel feedstock type had minimal impact on emissions, indicating the industrial oilseeds had similar performance to the traditional feedstocks. Fuel pathway did have an effect on emissions.

The emissions of carbon monoxide for the engine testing are shown in Fig. 7. The biodiesels had a reduction in CO emissions

Table 4
Physical properties of test fuels.

FUEL TYPE	Density @ 20 °C (g/cm^3) Anton Paar DSM5000	Sound velocity @ 20 °C (m s^{-1}) Anton Paar DSM5000	Kinematic viscosity @ 40 °C (mm^2 s^{-1}) Anton Paar SVM3000	Lower heating value J g^{-1} IKA C200
DIESEL	0.8414	1372.89	2.3411	45,263
Carinata B100	0.8840	1427.49	5.7133	39,665
Carinata TGB	0.8817	1413.68	12.852	40,478
Carinata R100^1	0.8173	1351.23	1.8789	45,126
Carinata R100^2	0.8175	1351.15	1.894	44,611
Camelina B100	0.8877	1424.2	4.9297	38,982
Camelina TGB	0.8811	1398.09	8.9612	39,708
Camelina R100	0.7825	1359.79	3.4835	44,911
Pennycress B100	0.8938	1437.69	7.4914	39,631
Pennycress TGB	0.8797	1410.53	12.006	39,789
Soybean B100 (crude)	0.8845	1417.06	4.7385	39,451
Soybean B100 (RBD)	0.8858	1419.01	4.9638	39,400
Soybean TGB (crude)	0.8744	1377.89	7.8246	39,646
Soybean TGB (RBD)	0.8801	1396.42	9.407	40,575
Corn B100 (RBD)	0.8924	1421.61	5.0825	39,519
Corn TGB (RBD)	0.8795	1397.76	9.3253	41,150
Corn TGB (crude)	0.8847	1419.42	8.3201	39,629
Canola B100	0.8754	1391.28	6.3684	40,459
Canola TGB	0.8946	1424.97	10.011	39,666
Sunflower B100	0.8846	1406.31	5.4996	39,838
Sunflower TGB	0.8750	1375.83	11.752	39,672

Notes:
B100 = 100% biodiesel
R100 = 100% renewable diesel
TGB = triglyceride blend (75% oil + 25% gasoline by volume)
RBD = refined, bleached, deodorized

Subscripts:
1 = heavy blend
2 = full boiling range

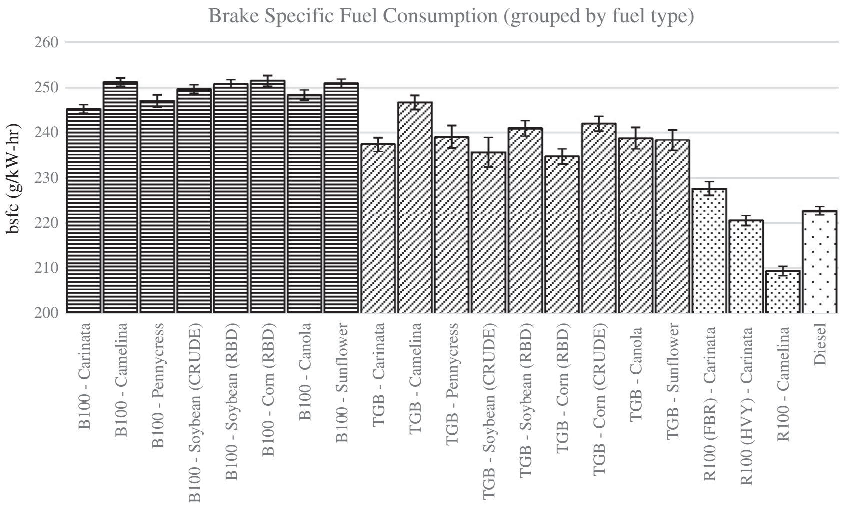

Fig. 5. Brake specific fuel consumption (grouped by fuel type).

compared to petroleum diesel, which is common for biodiesel use [58]. The renewable diesels also had slight reductions as compared to petroleum. The TGB biofuels had performance similar to diesel for most runs. For all emission measurements, the graphs indicate the median value of the three petroleum runs with the high and low values indicated by error bars. The errors bars indicate a small amount of variability in the three diesel runs for CO measurements.

The emissions of oxides of nitrogen for the engine testing are shown in Fig. 8. The biodiesels had a small increase in NOx emissions compared to petroleum diesel, which is common for biodiesel use [58]. The TGB and R100 biofuels had performance similar to diesel, or slight reductions for some runs. In one of the few categories of emissions where petroleum diesel typically outperforms biodiesel, the renewable diesel average was 6% lower for NOx emissions than petroleum. The errors bars indicate a small amount of variability in the three diesel runs.

The emissions of non-methane hydrocarbons (NMHC) for the engine testing are shown in Fig. 9. The biodiesels had similar or slight decreases in NMHC emissions compared to petroleum diesel. A decrease in NMHC emissions is common for biodiesel use, although emissions can vary with engine speed and load [58]. Some TGB biofuels had higher NMHC emissions than diesel. The R100 biofuels had performance similar to diesel. The errors bars indicate a higher amount of variability in the three diesel runs as compared to other emission measurements. There was no trending with time of day, or other known factors, that may have contributed to this increased variability over other emission measurements.

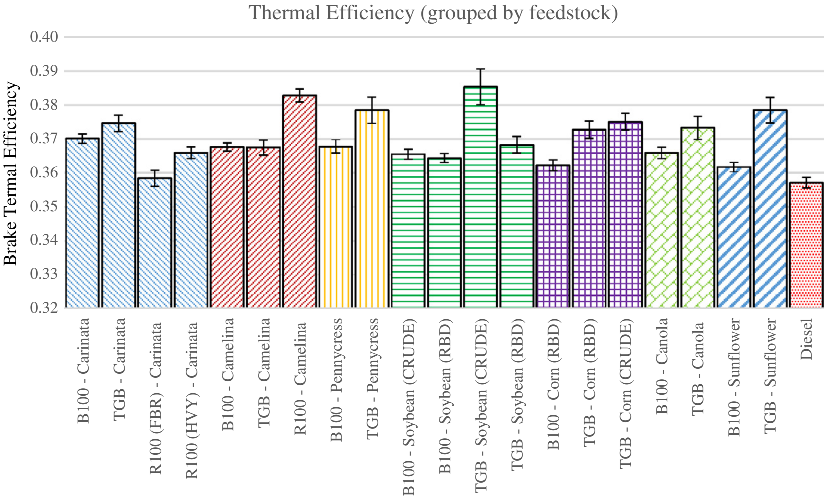

Fig. 6. Brake thermal efficiency.

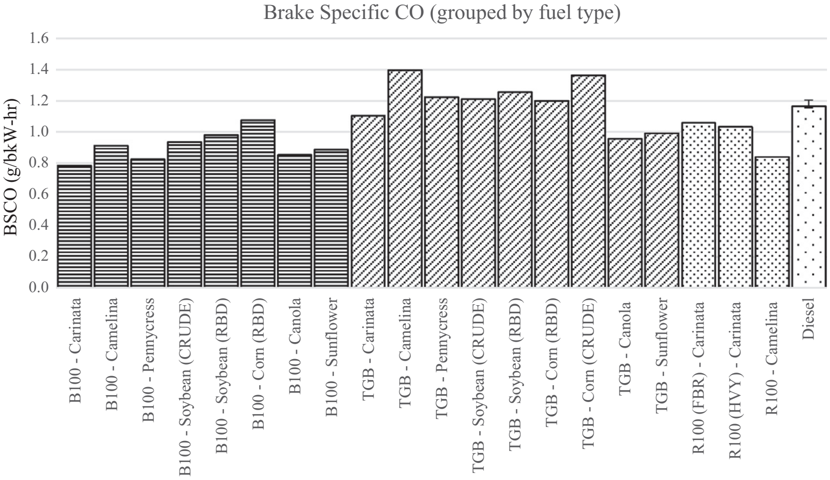

Fig. 7. Brake specific carbon monoxide results.

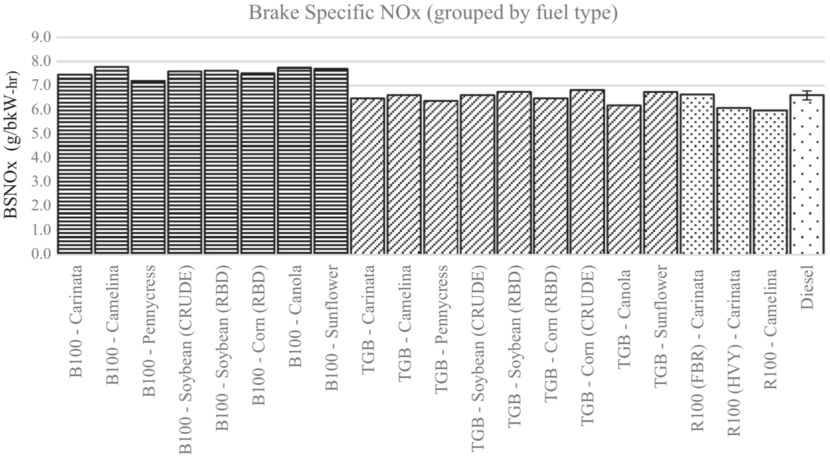

Fig. 8. Brake specific oxides of nitrogen (NOx) results.

The emissions of volatile organic compounds (VOCs) during the engine testing are shown in ppm in Fig. 10. The EECL's FTIR groups VOCs as non-methane, non-ethane, non-aldehydes hydrocarbons below C4. The biodiesels had slight decrease compared to the other fuels. TGB and R100 emissions were similar to petroleum diesel. VOCs can create photochemical smog under certain conditions,

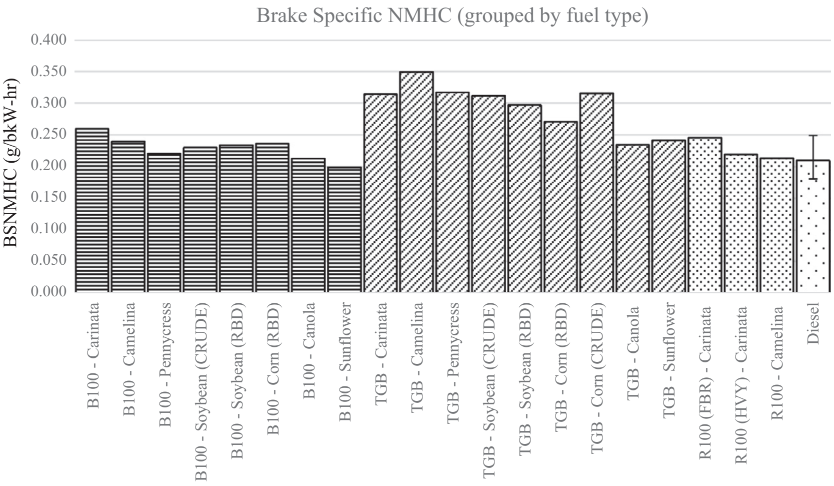

Fig. 9. Brake specific non-methane hydrocarbon results.

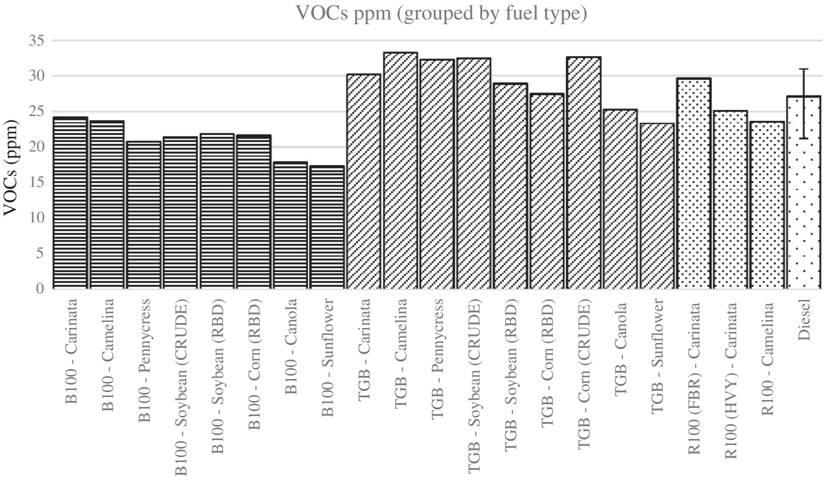

Fig. 10. Emissions of volatile organic compounds.

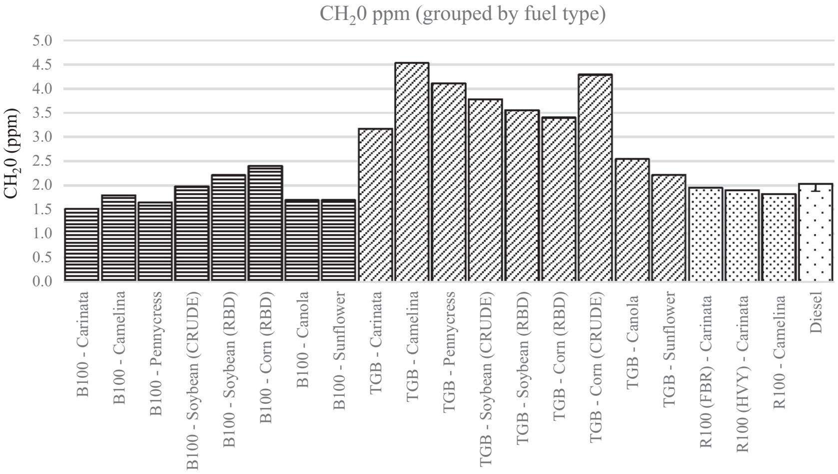

Fig. 11. Emissions of formaldehyde.

so it important that biofuels have similar or reduced VOC emissions as petroleum diesel [59].

The emissions of formaldehyde (CH_20) during the engine testing are shown in ppm in Fig. 11. B100 and R100 emissions were similar to petroleum diesel. The TGB biofuels had increased emissions of CH_20 as compared to the other fuels. The gasoline used as a blending agent for the TGB fuels contained 10% ethanol (E10). Ongoing TGB testing at the EECL will evaluate ethanol's contribution to formaldehyde and other emissions by sweeping ethanol in the blend from 0% to 85% (E85). Despite the increase for the

TGBs, the overall levels were small, with all test runs less than 5 ppm.

The remaining hydrocarbons measured by the FTIR were all small in concentration, and did not show significant differences between feedstocks or fuel pathways.

3.4. Particulate matter results

Particulate matter (PM) measurements included total mass emissions (g/hr), elemental carbon (EC) to organic carbon (OC) ratio, and particle size distribution using a scanning mobility particle sizer (SMPS).

Total PM mass emissions were measured gravimetrically via collection onto Teflon filters. The resulting brake specific particulate matter results are shown in Fig. 12. At this engine load and speed, most biofuels had PM emissions slightly higher than petroleum diesel. Typically, biofuels use shows a reduction in PM emissions [58]. Due to limited feedstock availability, data collection was limited to 5 min points and the resulting PM collected was near the limit of quantification (LOQ) for each run. Increased run times during future testing will increase the understanding of PM emission from these feedstocks and fuel pathways. PM emissions can also change with engine operating parameters; further study using additional engine operating points would also give a better comparison of feedstock and fuel types with respect to PM emissions.

Elemental carbon (EC) and organic carbon (OC) were measured via collection on quartz filters, which were subsequently analyzed using a Sunset Labs OC/EC Analyzer. Unfortunately, due to the small amount of PM collected on the quartz filters during each run, all the measurements were above the LOQ.

A Grimm Technologies Sequential Mobility Particle Sizer (SMPS) was used to measure particle size distributions from 10 to 1000 nm (nm) – note that in the subsequent figure, the distribution is only shown to 100 nm for increased resolution. In general, each fuel feedstock and type produced trends in size and distribution that were similar to petroleum. Fig. 13 shows the results for soybean biofuels. There was no significant difference in crude and refined fuel particle results for the soybean biodiesel runs, but a small reduction in peak particle count for the RBD TGB run.

3.5. Heat release results

A high speed pressure transducer was installed in the glow plug port of cylinder 1 as described in Section 2.2. The in-cylinder high speed pressure data can be plotted as a function of crank angle. The known geometry of the cylinder and connecting rod can then be used to calculate the cylinder volume as a function of crank angle. Pressure versus volume curves can then be used to calculate the apparent rate of heat release (J/deg) due to fuel combustion in the cylinder. A low pass Inverse Chebyshev filter was used to filter the oscillations due to the time derivative of pressure in the heat release curves.

Standard injection timing for this engine was used during testing. Except during startup, the John Deere 4045 test engine uses a single injection event. The engine ECU uses a lookup table based on throttle position, engine speed, and engine temperatures to determine injection timing. Even though the same engine speed and torque set points were used for each run, there were small injection timing differences due to differences in physical properties of fuels [60] and small fluctuations in operating conditions. The injection timing averages for each fuel type are shown in Table 5. The R100 runs had injection timing similar to petroleum diesel. The B100 and TGB biofuels both had slight injection delays of 0.70° and 0.92° respectively.

The heat release curves of the biofuels were similar to petroleum diesel with a few differences. Fig. 14 shows the results for carinata biofuels, as compared to petroleum diesel. The peak of the heat release profile is slightly smaller for the biofuels. Reductions in the peak rates of heat release were expected due to the lower energy contents of the biofuels [61]. The B100 and TGB heat releases are very similar. The renewable diesel peak is more similar in peak and shape to petroleum than the other biofuels.

The heat release curves for the soybean biofuels as compared to petroleum diesel are shown in Fig. 15. The trends in fuel type are

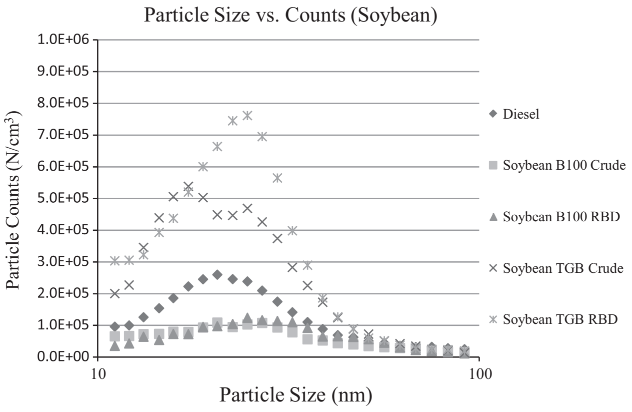

Fig. 13. Particle size versus counts – soybean feedstock.

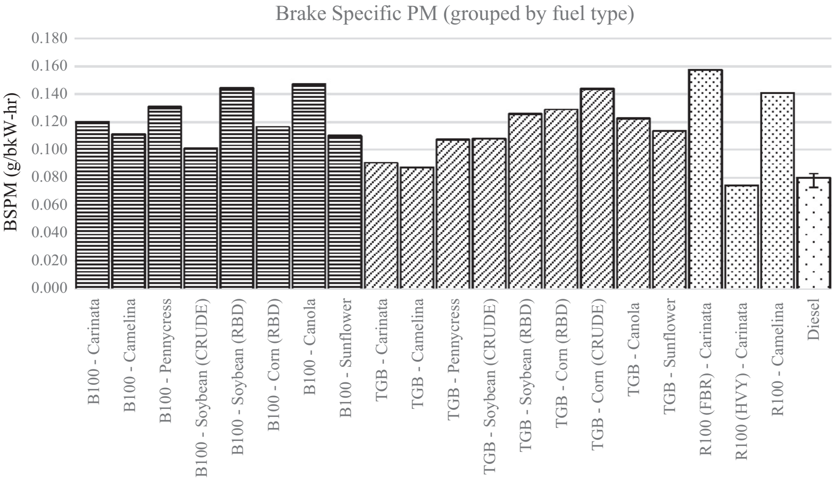

Fig. 12. Brake specific particulate matter.

Table 5
Injection timing of test fuels.

Injection timing		
Fuel type	Average (°BTDC)	Coefficient of variance (%)
Diesel	3.195	2.70
R100	3.259	2.83
B100	2.492	5.12
TGB	2.272	5.55

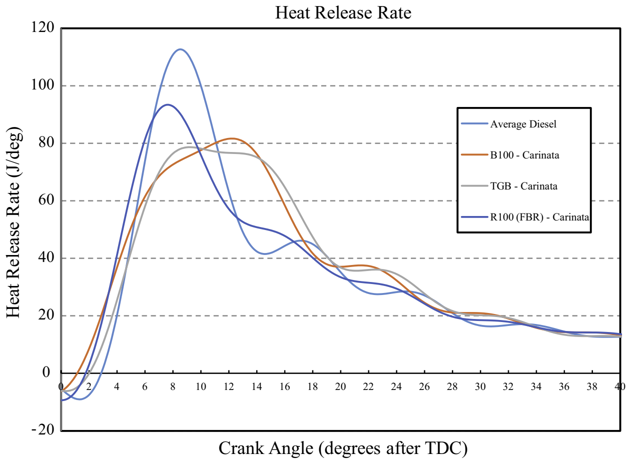

Fig. 14. Heat release of carinata biofuels.

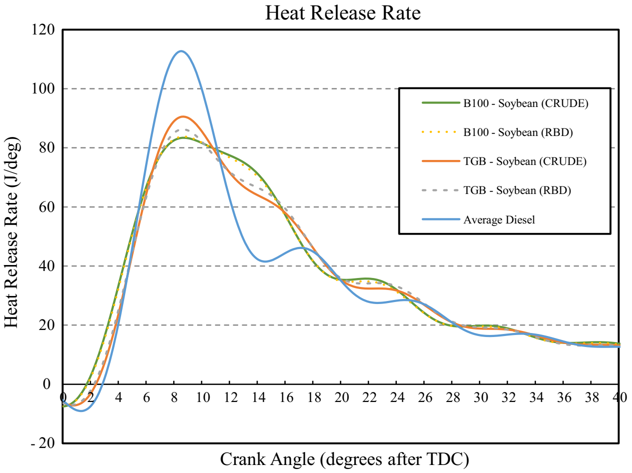

Fig. 15. Heat release of soybean biofuels.

similar to the carinata results in Fig. 14. The refinement level of the vegetable oil feedstock did not have a significant effect on the heat release curves. The crude and RBD results were very similar.

The location of 10% mass fraction burn duration is shown in Fig. 16. The test engine was insensitive to fuel type, with similar results for each fuel pathway. The 50% and 10–90% burn duration were also analyzed, and similarly did not show major differences between fuel pathway or feedstock.

4. Conclusions

Industrial oilseeds camelina, carinata, and pennycress had very similar engine performance to the traditional oils in this evaluation. Fuel consumption, thermal efficiency, and emissions were all were typical as compared to traditional oilseed feedstocks. For example, average bsfc for the industrial oilseed biofuels was within ±1.3% of the conventional oilseed biofuels for each fuel type. A recent camelina biodiesel conversion study found camelina biodiesel did not meet ASTM D6751 standards for cetane number, distillation temperature, and oxidation stability, which was suggested as serious drawbacks for camelina as a biodiesel feedstock [62]. However, this engine performance study found no engine operability, performance, or emissions issues when using camelina fuels or significant differences from the other feedstocks. Durability testing would better quantify engine performance of using camelina biodiesel in the long term.

Fuel pathway did have small impacts on engine performance. The engine performance of TGBs was of special interest since they are easy to produce and inexpensive in farm scale scenarios. Overall engine performance was favorable in all categories tested. TGBs had lower fuel consumption and a higher thermal efficiency than biodiesel for each feedstock tested. For several performance categories, TGB performed similar to petroleum diesel. For example, the mean value for TGBs volumetric bsfc was only 1.9% higher than the petroleum runs. TGB combustion characteristics were similar to biodiesel. Initial research with TGBs indicate it may be an ideal candidate for farm scale fuel production, which will bridge the gap for these industrial oils until the commercial market matures. The farm scale fuel production procedures (i.e. crude oil, no pretreatments) did not negatively affect engine performance or emissions in a modern Tier 3 CI engine. Besides the on-farm use, TGBs may also be an ideal fuel pathway for using locally produced plant oils worldwide in other niche markets, such as rural areas or in developing nations.

Biodiesel is also a viable fuel pathway for farm-scale scenarios. Biodiesel use offers several emission benefits. Biodiesel runs had reductions in CO, NMHC, VOC, and CH_20 emissions as compared to TGB runs. Biodiesel performance is much better understood than TGBs during long term use. Most engine manufactures also certify

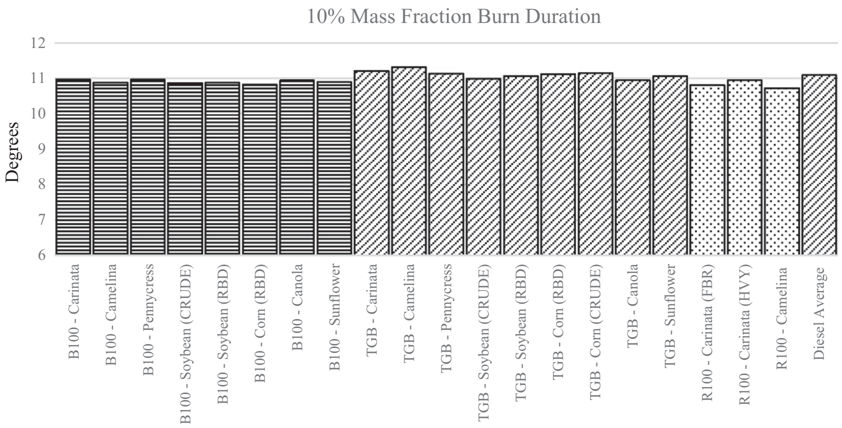

Fig. 16. 10% Mass fraction burn duration for test fuels.

their engines biodiesel compatible, which may be a major factor for farmers using modern equipment under warranty when choosing between biodiesel and TGB options.

The renewable diesels in the evaluation had performance as good as or better than petroleum diesel in nearly category. These fuels are intended as ‘‘drop-in’’ alternatives, and this study shows they meet their goal. The renewable diesels offer petroleum-like engine performance and combustion characteristics, while still maintaining some of the benefits of biodiesel such as reduced CO emissions. NOx emissions were also 6% lower for renewable diesel runs than petroleum.

Additional studies will investigate TGB fuel properties for multiple blend ratios. This study used a 75% vegetable oil to 25% gasoline volumetric ratio, which was compatible with a modern CI engine without modification. An extensive fuel property evaluation will indicate how important fuel properties like density, viscosity, flash point and cold flow characteristics change with TGB blend ratio. Future engine testing at the EECL will also change ethanol content in the gasoline, to quantify ethanol’s effect on engine performance. While the initial engine performance testing was favorable, on-going long-term durability testing at the EECL will assess the impact of using TGBs in the combustion chamber, fuel system, and after-treatment components as compared to using SVO, biodiesel, and petroleum diesel fuels.

Acknowledgments

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References

[1] U.S. EPA – Office of Transportation and Air Quality. Renewable Fuel Standard, Washington, DC: U.S. Environmental Protection Agency; 2013.

[2] Secretary of the Air Force Installations, Environment and Logistics. Air Force Energy Plan 2010, Washington, DC: U.S. Air Force; 2010.

[3] Blakeley K. DOD alternative fuels: policy, initiatives and legislative activity, Washington. DC: Congressional Research Service; 2012.

[4] U.S. Energy Information Administration. Sales of Distillate Fuel Oil by End Use, Washington, DC: U.S. Department of Energy; 2012.

[5] Skalsky SA, Jacobs JJ, Menkhaus DJ, Stevens WB. Impact of fuel and nitrogen prices on profitability of selected crops: a case study. Agron J 2008;100(4):1161–5.

[6] Hanna M, Harmon J, Flammang J. How much energy is used on your farm? Ames. IA (USA): Iowa State University Extension; 2009.

[7] U.S. Department of Agriculture. Impacts of higher energy prices on agriculture and rural economics, Washington, DC: U.S. Department of Agriculture; 2011.

[8] Fuls J, Hawkins CS, Hugo FJC. Tractor engine performance on sunflower oil fuel. J Agric Eng Res 1984;30:29–35.

[9] Keske CMH, Hoag DL, Brandess A, Johnson JJ. Is it economically feasible for farmers to grow their own fuel? A study of camelina sativa produced in the western United States as an on-farm biofuel. Biomass Bioenergy 2013;54:89–99.

[10] Uri ND, Day K. Energy efficiency, technological change, and the dieselization of American agriculture in the United States. Transport Plan Techn 1992;16(3):221–31.

[11] Paulsen HM, Wichmann V, Schuemann U, Richter B. Use of straight vegetable oil mixtures of rape and camelina as on farm fuels in agriculture. Biomass Bioenergy 2011;35:4015–24.

[12] Zhang Y, Dube MA, McLean DD, Kates M. Biodiesel production from waste cooking oil: economic assessment and sensitivity analysis. Bioresour Technol 2003;90:229–40.

[13] McIntosh CS, Smith SM, Withers RV. Energy balance of on-farm production and extraction of vegetable oil for fuel in the United States’ inland northwest. Energy Agric 1984;3:155–66.

[14] Berrios M, Martín MA, Chica AF, Martín A. Purification of biodiesel from used cooking oils. Appl Energy 2011;88:3625–31.

[15] National Agricultural Statistics Service. Agricultural Prices, Washington. DC: U.S. Department of Agriculture; 2013.

[16] Hill J, Nelson E, Tilman E, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS of the United States of America 2006;103(30):11206–10.

[17] Carolan MS. The cost and benefits of biofuels: a review of recent peer-reviewed research and a sociological look ahead. Environ Rev 2009;11:17–24.

[18] Brown RC, Brown TR. Why are we producing biofuels? 1st ed. Ames, IA: Brownia; 2000.

[19] Fröhlich A, Rice B. Evaluation of camelina sativa oil as a feedstock for biodiesel production. Ind Crop Prod 2005;21:25–31.

[20] Bernardo A, Howard-Hildige R, O’Connell A, Nichol R, Ryan J, Rice B, et al. Camelina oil as a fuel for diesel transport engines. Ind Crop Prod 2003;17:191–7.

[21] Crowley JG. Evaluation of camelina satvia as an alternative oilseed crop, Dublin. Ireland: Teagasc; 1999.

[22] Moser BR. Camelina (*camelina sativa* l.) oil as a biofuels feedstock: golden opportunity or false hope? Lipid Technol 2010;22(12):270–3.

[23] Moser BR, Vaughn SF. Evaluation of alkyl esters from camelina sativa oil as biodiesel and as blend components in ultra low-sulfur diesel fuel. Bioresour Technol 2010;101:646–53.

[24] Putnam DH, Budin JT, Field LA, Breene WM. Camelina: a promising low-input oilseed. In: Janick J, Simon JE, editors. New crops. New York: Wiley; 1993.

[25] Shonnard DR, Williams L, Kalnes TN. Camelina-derived jet fuel and diesel: sustainable advanced biofuels. Environ Prog Sustain Energy 2010;29:382–92.

[26] Moser BR, Knothe G, Vaughn SF, Isbell TA. Production and evaluation of biodiesel from field pennycress (*Thlaspi arvense* L.) oil. Energy Fuels 2009;23:4149–55.

[27] Evangelista RL, Isbell TA, Cermak S. Extraction of pennycress (*Thlaspi arvense* L.) seed oil by full pressing. Ind Crop Prod 2012;37:76–81.

[28] Cardone M, Mazzoncini M, Menini S, Rocco V, Senatore A, Seggiani M, et al. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterifcation and characterization. Biomass Bioenergy 2003;25:623–36.

[29] Hartman BJ. The renewable fuel standard: food versus fuel. Maine Law Rev 2013;65(2):540–1.

[30] Harison L. Carinata: a crop with potential for Florida’s Farmers, Gainesville. FL (USA): University of Florida Institute of Food and Agricultural Sciences Extension; 2013.

[31] Fan J, Shonnard DR, Kalnes TN, Johnsen PB, Rao S. A life cycle assessment of pennycress (*Thlaspi arvense* L.) – derived jet fuel and diesel. Biomass Bioenergy 2013;55:87–100.

[32] Sustainable Oils. Sustainable Oils Produces Camelina-based Fuel for Historic U.S. Air Force Flight, Bozeman, MT (USA): Sustainable Oils; 2010.

[33] Agrisoma Biosciences. Agrisoma Resonance Energy Feedstock Powers the World’s First 100% Biofuel Flight, Ottawa, Canada: Agrisoma Biosciences; 2012.

[34] U.S. Air Force Chief Scientist. Energy Horizons, Washington, DC: U.S. Air Force; 2012.

[35] U.S. Air Force Research Laboratory. Defense Production Act Title III Advanced Drop-In Biofuel Production Project Announcement, WPAFB, OH (USA): U.S. Air Force Research Laboratory Materials and Manufacturing Directorate; 2012.

[36] Shay EG. Diesel fuel from vegetable oils: status and opportunities. Biomass Bioenergy 1993;4:227–42.

[37] Ma F, Hanna MA. Biodiesel production: a review. Bioresour Technol 1999;70:1–15.

[38] Bajpai S, Sahoo PK, Das LM. Feasibility of blending karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine. Fuel 2009;88:705–11.

[39] Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Dimaratos AM, Founti MA. Comparative environmental behavior of bus engine operating on blends of diesel fuel with four straight vegetable oils of Greek origin: sunflower, cottonseed, corn and olive. Fuel 2011;90(11):3439–46.

[40] Schwab AW, Bagby MO, Freedman B. Preparation and properties of diesel fuels from vegetable oils. Fuel 1987;66:1372–8.

[41] Franco Z, Nguyen QD. Flow properties of vegetable oil–diesel fuel blends. Fuel 2011;90:838–43.

[42] Basinger M, Reding T, Williams C, Lackner KS, Modi V. Compression ignition engine modifications for straight plant oil fueling in remote contexts: modification design and short-run testing. Fuel 2010;89:2925–38.

[43] Dorado MP, Arnal JM, Gómez J, Gil A, López FJ. The effect of a waste vegetable oil blend with diesel fuel on engine performance. Trans ASAE 2008;45:519–23.

[44] Peterson CL, Wagner GL, Auld DL. Vegetable oil substitutes for diesel fuel. Trans ASAE 1983;26:322–32.

[45] Adams C, Peters JF, Rand MC, Schroer BJ, Ziemke MC. Investigation of soybean oil as a diesel fuel extender: endurance tests. J Am Oil Chem Soc 1983;60:1574–9.

[46] Schlautman NJ, Schinstock JL, Hanna MA. Unrefined expelled soybean oil performance in a diesel engine. Trans ASAE 1986;29:70–3.

[47] Kibbey TCG, Lixia C, Do LD, Sabatini DA. Predicting the temperature-dependent viscosity of vegetable oil/diesel reverse microemulsion fuels. Fuel 2014;116:432–7.

[48] Srivastava A, Prasad R. Triglycerides-based diesel fuels. Renew Sust Energ Rev 2000;4:111–33.

[49] Balat M, Balat H. A critical review of bio-diesel as a vehicular fuel. Energ Convers Manage 2008;49:2727–41.

[50] Dunn RO, Bagby MO. Low-temperature phase behavior of vegetable oil/co-solvent blends as alternative diesel fuel. J Am Oil Chem Soc 2000;77:1315–22.

[51] Dunn RO, Bagby MO. Low-temperature flow properties of vegetable oil/co-solvent blends as alternative diesel fuel. J Am Oil Chem Soc 2002;79:709–15.

[52] Lakshminarayanan A, Olsen DB, Cabot PE. Performance and emission evaluation of triglyceride-gasoline blends in agricultural compression ignition engines. Appl Eng Agric 2014;30.

[53] Marillia EF, Francis T, Falk KC, Smith M, Taylor DC. Palliser's promise: *Brassica carinata*, an emerging western Canadian crop for delivery of new bio-industrial oil feedstocks. Biocatal Agric Biotechnol 2014;3:65–74.

[54] Bennett M, Volckens J, Stanglmaier R, McNichol AP, Ellenson WD, Lewis C. Biodiesel effects on particulate radiocarbon emissions from a diesel engine. Aerosol Sci 2008;39:667–78.

[55] Li L, Coppola E, Rine J, Miller JL, Walker D. Catalytic hydrothermal conversion of triglycerides to non-ester biofuels. Energy Fuels 2010;24:1305–15.

[56] ISO 8178–4, Geneva, Switzerland: International Organization for Standardization; 2007.

[57] Jaichandar S, Annamalai K. The status of biodiesel as an alternative fuel for diesel engine. J Sustain Energy Environ 2011;2:71–5.

[58] U.S. Environmental Protection Agency. A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Washington, DC: U.S. EPA Office of Transportation and Air Quality; 2002.

[59] U.S. Environmental Protection Agency, Volatile Organic Compounds (VOCs) Technical Overview, U.S. EPA, Washington, DC, 2012.

[60] Ali Y, Hanna MA, Borg JE. Effect of alternative diesel fuels on heat release curves for cummins N14–410 diesel engine. Trans ASAE 1996;39:407–14.

[61] Tat ME, Van Gerpen JH. Measurement of Biodiesel Speed of Sound and Its Impact on Injection Timing. National Renewable Energy Laboratory Report SR-510-31462; 2003: 1–30.

[62] Ciubota-Rosie C, Ruiz JR, Ramos MJ, Pérez A. Biodiesel from *Camelina sativa*: a comprehensive characterisation. Fuel 2013;105:572–7.