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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].

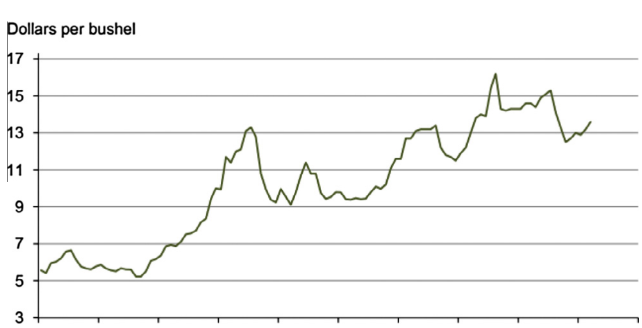

Fig. 1. U.S. prices received for soybeans [15].

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)