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Fuel properties, performance testing and economic feasibility of *Raphanus sativus* (oilseed radish) biodiesel

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A B S T R A C T

Oilseed radish (*Raphanus sativus*) was identified as a potential cool season cover and energy crop for the southern United States. The fatty acid profile of this oil shows high levels of erucic acid (C22:1), which has been linked to health issues. Its composition makes this oil an ideal candidate for industrial application as its use as feed or food is limited. Oilseed radish oil was extracted from seed using mechanical methods and yields were determined. The extracted oil was converted to fatty acid methyl esters (biodiesel) via transesterification. Fuel properties were analyzed including fatty acid profile, free and total glycerol, acid number, sulfur content, water content and cold filter plugging point (CFPP). Fuel properties of the biodiesel were found to meet or exceed ASTM standards for use in on-road vehicles. Biodiesel fuel produced here was also subjected to an engine performance stress test. The properties and engine performance of oilseed radish biodiesel were shown to be comparable with No. 2 diesel and other common biodiesel fuels. Additionally, a brief engineering based feasibility analysis was performed on the economics of on-farm production of biodiesel from oilseed radish. The analysis suggested economic feasibility of the system when priced against soybean oil, a common biodiesel feedstock.

1. Introduction

Traditionally, soybeans have provided the main source of lipid feedstock for biodiesel production in the United States. Other crops used for this purpose include, but are not limited to, peanut, sunflower, and canola. The use of these crops for biodiesel production has caused the perception of competition with their food-based markets and thus a price increase in the vegetable oils from these crops (Ma and Hanna, 1999). The largest single cost in biodiesel production is feedstock, which accounts for approximately 80 percent of biodiesel production (McIntosh et al., 1984). This presents a problem if traditional oilseed crops are to be used for on-farm biodiesel production as their food market value generally exceeds their value as a fuel. Furthermore, growing oilseed crops to produce fuel in the warm season competes with traditional cash crops. An oilseed crop grown in the cool season would not compete with traditional economic crops, and if kept behind the farm gate, could provide a cost-effective source of lipids and biomass for industrial applications such as biofuel production.

Crop rotations are used to maintain soil fertility while decreasing the reliance on fertilizers (Yunusa and Rashid, 2007). Cover crops are grown in the cool season after major economic crops are harvested. They serve as green manure to restore nutrients to the soil, aid in combating soil pathogens for the next crop, and to prevent erosion (Larkin and Griffin, 2007). Currently these crops are of economic importance only in the manner that they reduce the costs of fertilizer, pesticides, and erosion control on the farm; the crops are generally not sold in the marketplace as cash crops. Some oilseed crops, such as oilseed radish (*Raphanus sativus* ssp. *oleiferus*, in the *Brassica* family), rapeseed, and mustard, can provide many rotational and green manure benefits when grown as cover crops (Martins et al., 2012, Bunte et al., 1997). As an example, Lehrsch and Gallian (2010) showed oilseed radish biomass appeared to stabilize both infiltration and hydraulic conductivity from spring to fall. Additionally, radish treatment increased the infiltration rate and hydraulic conductivity through pores ≤0.75 mm at and below the soil surface season-long, compared to the control. These crops contain comparable levels of seed oil content to that of traditional oilseed crops such as soybean and peanut. Oilseed radish may contain up to 40% oil in its seed (Eckey, 1954). This crop has been grown as a cool season cover crop in the US and has been shown to have favorable effects in aiding in control of plant pathogens (Lazzeri et al., 2004). Recent work by de Andrade Ávila and Sodré (2012) examined forage radish as a biodiesel feedstock. This work showed elevated acid and sulfur content exceeding Brazilian, US and EU standards. This study sought to determine if oilseed radish oil exceeded the standard values for these parame-

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ters as well. While both cultivars are *R. sativus* ssp. *oleiferus*, the two cultivars have different fatty acid profiles, which was predicted to lead to a differentiation in fuel properties between the two oils.

Since biodiesel has been produced on a large scale, certain favorable fuel properties have been established to evaluate potential fuels from new feedstocks (Ali and Hanna, 1995). Fuel performance criteria have also been established when biodiesel fuels are used in diesel engines (Korus et al., 1985 and Goodrum et al., 1996). Biodiesel fuels made from cool season crops in the *Brassica* family, such as canola, have shown comparable performance to No.2 diesel (Schumacher and Van Gerpen, 2007).

A hurdle in the implementation of biodiesel on a larger scale is the high price of vegetable oil feedstocks obtained from traditional crops (CAED-CAES, 2007). A less expensive, industrial oil feedstock is needed that does not compete with food crops grown during the economic growing season. Cool season oilseed cover crops have the potential to serve as a lower-cost vegetable oil feedstock, while maintaining the agronomic and economic benefits of cool season cover crops. We hypothesized that if oilseed radish were shown to be viable in the cool season of the southern US, its oil would produce an acceptable biodiesel fuel. This prediction was based on data that showed oilseed crops within the *Brassica* family, such as canola and rapeseed, produced quality biodiesel as a substitute for diesel fuel (Kulkarni et al., 2007).

In this study, oilseed radish seed was obtained and crushed to produce oil. The oil was transesterified into biodiesel and biodiesel properties and engine performance were analyzed and compared with the properties of other biodiesel fuels. Based on the data collected here, a brief economic feasibility analysis was performed on the system.

2. Materials and methods

2.1. Oil extraction and preparation of oilseed radish biodiesel

A total of 90 kg (200 lbs) of seed was obtained from Johnny's Select Seeds of Winslow, Maine and crushed (150 °C, 60 Hz) using a model ZY-12C screw type oil press (Shanghai Xuyi Machinery Company, Shanghai, China) to obtain the oil. Oil was filtered through a metal mesh screen and centrifuged in a US centrifuge model M212 centrifuge to obtain the clarified oil for further testing.

Several preliminary experiments with varying reaction stages (one or two): number of total reactions (one or two), and washing methods were conducted to identify the optimal transesterification procedure. As reported below, the acid number of the cold pressed oil was determined to be 2.16 mg/g. Based on this number the conversion used 9 g-KOH/L-oil and 0.20 L-methanol/L-oil. Methanol and KOH were mixed prior to transesterification. The first reaction was a two-stage reaction utilizing 85% of the KOH/methanol in the first stage and the remaining 15% in the second stage. In each stage of the reaction the reactants were mixed at 270 rpm on a heated stir plate for one hour maintaining a temperature range of 50–60 °C. The biodiesel was allowed to settle in a separatory funnel for one hour after which time crude glycerine was decanted from the bottom of the funnel. Product was washed 3× by mixing water (10 mL-water/100 mL-biodiesel) and biodiesel for 1.5 min at 170 rpm. After each wash the water was separated from the biodiesel using a separatory funnel as described above. After the third wash of the second stage, the biodiesel was heated on a stir plate at 100 °C, and a second, one stage conversion was conducted using 9 g-KOH/L-biodiesel and 0.20 L-methanol/L-biodiesel. After glycerine was decanted, fuel was washed 4× using 10% water and fuel was dried on a heated stir plate at 100 °C until all water was evaporated as described in the previous step.

Table 1
Oilseed radish B100 fuel properties.

Parameter	Unit	Test method	Result	Limit
Total glycerol	% (m/m)	EN 14105	0.108	≤0.24
Free glycerol	% (m/m)	EN 14105	0.000	≤0.02
Monoglyceride content	% (m/m)	EN 14105	0.301	≤0.80
Diglyceride content	% (m/m)	EN 14105	0.027	≤0.20
Triglyceride content	% (m/m)	EN 14105	0.000	≤0.20
Acid Value	mgKOH/g	EN 14104	0.082	≤0.50
Sulfur content	mg/kg	EN ISO 20846	0.79	≤10.00
Water content	mg/kg	EN ISO 12937	68	≤500
Iodine value	g/100 g	EN 14111	97	≤120
Cold Filter Plugging Point (CFPP)	°C	ASTM 637199	6.0	Report

2.2. Fuel property analysis of oilseed radish biodiesel

All analyses were performed at US Biofuels, Inc. laboratories (Rome, GA). Fatty acid profile was determined by gas chromatography using the method of Park and Goins (1994). United States (ASTM) and European (EN) fuel quality analysis was conducted using standard ASTM and EN methods.

2.3. Engine performance testing of oilseed radish biodiesel

Engine performance was evaluated using the methods described in Geller et al. (1999) and Goodrum et al. (1996). In brief, two identical single cylinder, direct injection, Kubota diesel engines were used in the analyses. Each fuel test consisted of a baseline using standard No. 2 diesel fuel (ultra-low sulfur on-road diesel fuel), followed by three B100 fueled runs, with a final No. 2 diesel run. A coking index (CI) is reported for each analyzed fuel. CI is the ratio of coke accumulated on injector tips during a run with the fuel of interest to the amount of coke accumulated using No. 2 diesel fuel. A coking index > 1.0 indicates degraded performance while an index < 1.0 indicates improved performance over No. 2 diesel fuel (Goodrum et al., 1996).

2.4. Economic analysis

Costs and returns were calculated on a per acre basis using the low-end yield data obtained from previous experiences of growers in the Willamette Valley of Oregon (personal communication) who reported yields of 1345–2242 kg/ha (1200–2000 lb/acre). The costs and returns calculated are estimated costs and returns based on available data from various sources. The costs calculated here assume low input cultivation, i.e. planting and harvesting the crop only. Estimated returns were calculated from crop and biodiesel byproducts, and from insecticide cost savings based on the nematode controlling properties of oilseed radish (Bunte et al., 1997).

3. Results and discussion

3.1. Extraction yield and fuel properties of oilseed radish biodiesel

The results of analysis for oilseed radish biodiesel fuel properties are presented in Table 1. The biodiesel produced from oilseed radish in this experiment met or exceeded all limits outlined in the ASTM specification. Of special significance are two crucial fuel quality properties; iodine value and cold filter plugging point (CFPP). These properties are dependent on feedstock, not production method. As a point of reference, soybean biodiesel has an iodine value of 131.6 (Eckey, 1954) and a CFPP of −2 °C (Mittelbach and Remschmidt, 2005). Soybean biodiesel does not meet the iodine value limit of 120 g/100 g required in the European standard. Soybean biodiesel does have a favorable CFPP that would allow its use in colder climates. However, the high iodine value of soybean