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The influence of straight vegetable oil fatty acid composition on compression ignition combustion and emissions

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HIGHLIGHTS

- Combustion and emissions of 7 vegetable oils (SVO) including one from micro-algae.
- Tested in a common-rail direct injection compression ignition engine.
- Strong correlation of SVO mean fatty acid degree of saturation with ignition delay.
- Heat release rates increase with oil viscosity due to fuel impingement.
- Particulate emissions are affected by fatty acid molecular structure and viscosity.

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ABSTRACT

This paper presents experimental studies carried out on a modern direct injection compression ignition engine supplied with a range of straight vegetable oils to investigate the effect of oil fatty acid composition on combustion and emissions. Seven oils, those of corn, groundnut, palm, rapeseed, soybean, sunflower and the micro-algae species *Chlorella protothecoides* were tested, with all of the fuels heated to 60 °C, at constant injection timing and constant ignition timing at a constant engine speed of 1200 rpm. All of the vegetable oils exhibited a duration of ignition delay within ±0.6 CAD of that displayed by a reference fossil diesel, but displayed much reduced rates of peak heat release rate. The duration of ignition delay was found to increase with an increasing carbon to hydrogen ratio of the vegetable oils, implicating the fatty acid alkyl chain as the primary driver of low temperature reactivity. Peak heat release rates decreased with decreasing vegetable oil viscosity, suggesting a significant degree of fuel cylinder wall and piston bowl impingement. At both injection timings, emissions of NO_x were lower for all of the vegetable oils relative to the reference fossil diesel, while those of CO, THC and particulate matter were higher and sensitive to the injection timing.

1. Introduction

Vegetable oils were amongst the first widely considered alternatives to liquid fossil fuels, and the products of transesterification of such oils with alcohols are now widely used as biodiesel. However, while the use of biodiesel does reduce tailpipe emissions of fossil bound carbon, which as carbon dioxide contribute to anthropogenic global warming, there are increasing concerns as to the sustainability of such biodiesels when considering the entirety of the fuel lifecycle [1]. Therefore, given that the conversion of vegetable oils to biodiesel requires an additional input of energy and materials (usually an alcohol in the form of fossil-derived methanol [2]), it is useful to re-examine the use of non-transesterified straight vegetable oils for the displacement of fossil fuels in the context of modern combustion technology.

In the early 1980s, concern as to the security of supply of fossil fuels saw the use of vegetable oils as a replacement investigated, especially in the context of agricultural usage [3,4]. Vegetable oils are predominately made up of triglycerides, molecules which consist of three fatty acids joined by a glycerol group. While the structure of the fatty acids that make up the triglycerides, and the level of each triglyceride species present, varies from oil to oil, it is the long alkyl chain present in the fatty acids that make the oils suitable for compression ignition combustion. However, the use of vegetable oils was found to compromise the durability of compression ignition engines, in particular by increased injector nozzle coking, piston ring sticking and dilution of the engine lubrication oil [3,5].

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Nomenclature

NO_x	nitrous oxides	SOI	start of injection
CO_2	carbon dioxide	BTDC	before top-dead-centre
CO	carbon monoxide	TDC	top-dead-centre
THC	total hydrocarbons	SOC	start of combustion
CAD	crank angle degree	IMEP	indicated mean effective pressure
PID	proportional integral derivative	PPM	parts per million
DAQ	data acquisition	FAME	fatty acid methyl ester
O_2	oxygen	SVO	straight vegetable oil

Ryan et al. [5] studied the combustion of several vegetable oils, at various stages of refinement, in a heated and pressurised constant volume chamber and also in direct and indirect compression ignition engines. In this study, all of the oils were heated from 40 °C to 145 °C so as to reduce the viscosity of oils to a level similar to that of a reference fossil diesel. It was expected by Ryan et al. that reducing fuel viscosity would increase fuel atomization on injection, and also decrease the penetration rate of the spray (rate of spray tip travel from the injector nozzle) with a concurrent increase in the cone angle of the spray. However, heating of the oils, while reducing viscosity, actually increased the penetration rate and decreased the cone angle. In combustion tests, the direct injection engine was found to both suffer more of the durability issues relative to the indirect injection engine and a greater sensitivity to the composition of the vegetable oils.

Transesterification of vegetable oils to fatty acid esters was found to diminish many of the durability issues encountered in the use of vegetables oils [6,7]. Nevertheless, use of straight vegetable oils, neat and blended with fossil diesel, has persisted [8–17]. There have been several reviews [18–21] on the use of vegetable oils, which have repeatedly highlighted the dependence of engine durability, combustion phasing and emissions production on fuel temperature and the subsequent physical properties of the vegetable oil.

Recently, there have been several studies which have sought to characterise the effect of heating on straight vegetable oils [22]. Franco and Nguyen [23] measured the dynamic viscosity of six vegetable oils, and found that at all temperatures (20–80 °C) the viscosity decreased with a decreasing degree of saturation of the fatty acid alkyl chains. The same observation was made by Santos et al. [24] who found a better correlation between viscosity and the level of alkyl chains containing more than two double bonds (polyunsaturates) than those containing only one double bond.

Deshmukh et al. [25] undertook optical spray characterisation of two vegetable oils of differing viscosity (pongamia and jatropha), utilising a single hole solenoid valve injector at an injection pressure of 1600 bar. For the spray characterisation, both oils were heated to 60 °C, and at a lower temperature of 40 °C the pongamia and jatropha oils exhibited dynamic viscosities of 37 mPa s and 30 mPa s respectively. Measurement of the injection delay was made (defined as the interval between commencement of injector actuating signal and the first appearance of fuel at the injector tip) and found to be of longer duration for the oil of higher viscosity (pongamia). Furthermore, the more viscous oil exhibited greater injection to injection variability in the duration of injection delay. This was attributed to the greater degree of resistance presented by the more viscous oil to the opening of the injector needle. Pongamia oil also exhibited a lower penetration rate relative to the less viscous jatropha oil, and it was suggested that the higher viscosity of the former reduced the momentum of the spray during injection.

Pinzi et al. [26] investigated the effect of vegetable oil fatty acid composition on the physical properties of the fatty acid methyl esters of the same vegetable oil. They found that the lower heating value, cetane number and kinematic viscosity of the fatty acid esters increased with the carbon chain length of the vegetable oil fatty acid alkyl chain and decreased with decreasing saturation. While the alkyl carbon chain length influenced most the lower heating value of the fatty acid esters, cetane number was most affected by the degree of saturation. Mehta and Anand [27] investigated the effect of fatty acid composition on vegetable oil lower heating value, and found a similar influence of alkyl chain carbon length and degree of saturation on lower heating value, with an increase in both properties raising the lower heating value of the vegetable oil.

This paper presents results of combustion experiments with six edible straight vegetable oils, and one non-edible oil from micro-algae, as un-blended fuels in a single-cylinder direct injection compression ignition engine, undertaken so as to develop scientific knowledge useful for the rapid screening of potential vegetable oil fuels. Combustion characteristics and emission levels are compared to a reference fossil diesel and the influence of the vegetable oil chemical and physical properties on these characteristics investigated.

2. Experimental methods

2.1. Apparatus

A modern direct injection diesel engine, converted to run as a single cylinder research engine, was utilised for all of the combustion experiments described in this work. As the straight vegetable oils under study possessed viscosities much higher than fossil diesel, and in the case of the oil from micro-algae available in very limited quantity, use was made of a novel low volume fuel system for high pressure direct injection (sample fuel volumes of 100–250 mL at injection pressures up to 1600 bar). This engine test facility, and the experimental methodology employed, has been described in detail by the author in previous studies [28,29]. For all experiments, the low volume fuel system and sample fuel lines were held at a constant temperature of 60 ± 2.5 °C, and the engine was normally aspirated with air at atmospheric temperature and pressure throughout. Table 1 gives further specifications of the engine, while Fig. 1 displays the operating principles of the low volume fuel system in schematic form.

In addition to measurement of the in-cylinder gas pressure, for all tests the composition of the engine exhaust gas was determined with an automotive gas analyser system (Horiba MEXA9100 HEGR) and a fast particulate spectrometer (Cambustion DMS 500), conducted at the sampling conditions described previously by the author [28,29].

2.2. Fuels investigated

Seven straight vegetable oils were tested so as to investigate the effect of natural oil fatty acid composition on compression ignition