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Full Length Article

Straight and waste vegetable oil in engines: Review and experimental measurement of emissions, fuel consumption and injector fouling on a turbocharged commercial engine

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HIGHLIGHTS

- Generally, specific fuel consumption decreases with power increasing.
- CO emissions decrease and NO_X emission increases with power increasing.
- Vegetable seeds oils specific consumption is 10–30% higher than diesel.
- Waste frying vegetable oils consumption is comparable to that of pure vegetable oils.
- Waste sunflower oil CO and NO emissions are comparable to those of pure vegetable oils.

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ABSTRACT

Biomass to energy conversion is an important action to reach sustainability, particularly on the small scale. Among different biomasses, however, vegetable oils can fire directly a compression ignited internal combustion engine with minimal pre-treatment of the fuel and adaptation of the engine. Energy production from waste cooking oils is even more interesting because it allows energy production while disposing of a residue. Data available in the Literature are rarely referring to commercially available engines therefore additional information is required on overall performance, emissions, and maintenance requirements.

This paper presents the results of tests carried out by fuelling a commercially available 33 kW direct injection Diesel engine with different fuels, such as: Diesel (used as benchmark), biodiesel, linseed oil, RBDPO (Refined, Bleached and Deodorized Palm Oil), corn oil, soy oil, peanuts oil, sunflower oil, palm oil, waste frying sunflower oil and waste frying palm oil. Tests were performed at three different loads (10, 20, 30 kW) measuring fuel consumption, electricity production and exhaust gases temperature and composition. Fuel injectors were checked following each test to evaluate the fouling caused by different fuels.

Results show that when increasing load fuel consumption shows a general decreasing trend while CO emissions decrease and NO_X increase. All fuels show a higher consumption than diesel, due to a lower calorific value. Biodiesel CO emissions decrease with power increasing with a lower slope than diesel, therefore are lower at the lowest power and higher at the highest power. Biodiesel NO emissions are always 15–20% higher than diesel.

Vegetable oil CO emissions are higher or lower than diesel ones depending on the power and on the fuel, while NO emissions are often higher than diesel ones. Specific fuel consumption, CO and NO emissions of waste frying vegetable oil are generally comparable to those of pure oils.

1. Introduction and state of the art

Biomass to energy conversion may represent a key action to reach sustainability decreasing global warming and fossil energy sources impoverishment. Pure vegetable oils and waste cooking vegetable oils are interesting fuels because they can be used

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Nomenclature

BFSC	Brake Specific Fuel Consumption (g/kWh)	LHV	Low Heating Value (kJ/kg)
BMEP	Brake Mean Effective Pressure (MPa)	HC	unburned hydrocarbon
BSEC	Brake Specific Energy Consumption	HHV	High Heating Value (kJ/kg)
BTE	Brake Thermal Efficiency (%)	M.E.P.	Mean Effective Pressure (bar)
CHP	Combined Heat and Power	RBDPO	Refined, Bleached and Deodorized Palm Oil
EGT	Exhaust Gases Temperature (°C)	rpm	round per minute (min^{-1})
FAME	Fatty Acid Methyl Ester	VO	Vegetable Oil
ICE	Internal Combustion Engine	WFO	Waste Frying vegetable Oil

directly in an engine to produce electricity, with low pretreatment required by the fuel and low adaptation required by the engines. Diesel, biodiesel, some vegetable oils and their blends behavior in engines were previously evaluated by other authors, however results are not coherent due to differences in engine size and experimental setup. The following section will address main experimental tests available in the Literature.

İlkılıça and Aydınb [1], Lapuerta et al. [2] Rakopoulos et al. [3] evaluated the performance and emissions of diesel–biodiesel blends in turbocharged and after cooled IC engines. All cases show a CO decrease with biodiesel content increasing, while NOx emissions decrease in small size engines [1,2] while increasing in [3] with biodiesel content; the Brake Specific Fuel Consumption (BSFC) increases in all cases. Yilmaz and Morton [4] analyzed the performances of two Diesel engines at variable loads fuelled with diesel–biodiesel blends considering different composition, namely B0 (diesel), B20 (20% biodiesel–80% diesel) and B100 (biodiesel). Tests showed that CO emissions decreased with increased loads.

Song et al. [5], Barrios et al. [6], Buyukkaya [7], Özener et al. [8], Shehata [9], Valente [10], Ozsezen et al. [11], Altun and Lapuerta [12], Lin and Lin [13], compared performance and emissions of biodiesel and diesel fuelled IC engines. Biodiesel fuelling increases BSFC about 7–10% while decreasing Brake Thermal Efficiency (BTE) [7,11]. NOx emissions increase from 12% to 30% [5,7] at full load and particulate emissions also up to 68% [11]. In many cases biodiesel causes a decrease of CO emissions compared to diesel emissions (from 32% to 87% with waste frying oil biodiesel [11]); but in [10] results show an increase in CO emissions with increasing biodiesel content from 5% to 85% in a soybean biodiesel blend. Beatrice et al. [14] compared emissions of diesel and soybean and rapeseed methyl-ester fuelling an Euro 5 CI engines on NEDC: in this case the methyl ester employment results in a slight reduction of HC emissions and 90% PM decrease. The work also reports an increase in both NOx (of 60%) and CO emission (mainly affected by low pilot combustion efficiency and delayed combustion timing at low load).

Other authors evaluated a Diesel engine fuelled with vegetable oils–diesel blends.

Rakopoulos et al. [15] fuelled a turbocharged and after-cooled direct injection diesel generator with diesel–vegetable oils blends, including sunflower oil, cottonseed oil, corn oil and olive oil. Authors founded that BTE with vegetable oil blends was the same of that with diesel. CO, unburned hydrocarbon and NOx emissions were slightly higher for vegetable oils than for diesel while emitted smoke was less. Moreover Leevijit and Prateepchaikul [16], Tüccar et al. [17], Devan and Mahalakshmi [18] evaluated diesel–vegetable oil blends performances: it was found that BTE decreases and BSFC increases (8% in [16] and 15% in [18]) at full load as greater amount of vegetable oil is blended. This same condition allows greater CO emission (increased up to 40% [16]) and smoke content reduction; in [16] NOx emissions present a minimum increment while in [18] they decrease (more evident at partial load, 32% of reduction at 25%).

Agarwal [19] reviewed the works of many authors on the production, characterization and experimental research on ICE fuelled with primary alcohols, ethanol–diesel blends, vegetable oil, micro emulsions and biodiesel. By comparing the use of diesel, biodiesel and raw vegetable oils he reports different results for CO and NOx emissions: in some cases an increase in CO and decrease in NOx with biodiesel and vegetable oil with respect to diesel is shown while other authors show an opposite trend for both pollutants. Some authors tested ICEs fuelled with straight vegetable oils.

Shehata and Razek [20] evaluated preheated (75 °C) sunflower oil combustion in an indirect injection Diesel engine connected to a hydraulic dynamometer with variable load. The study found that sunflower consumption increased by 5% with respect to diesel while unburned hydrocarbons emissions decreased by 34%, CO emissions increased between 4% and 7% at variable speed.

Altin et al. [21] tested a 770 cm^3 Diesel engine with different vegetable oils obtained from corn, rapeseed, sunflower, cotton, opium, and also the methyl esters derived from these oils. Test results show that diesel had lower fuel consumption (245 g/kWh) with respect to sunflower oil (290 g/kWh) and also the lower CO emissions (2225 ppm) when compared to rapeseed oil and corn oil with sunflower oil showing the highest value (close to 4000 ppm).

Nwafor [22] tested rapeseed oil in a 304 cm^3 Diesel engine preheated at 70 °C and at ambient temperature. CO emissions changed from 0.1% to 0.15% up to 0.4% with load increasing, but remained lower than those for diesel. Vegetable oil consumption was consistently higher than diesel.

Kleinová et al. [23] tested two diesel engine fitted cars (Skoda Octavia 1.9 TDI produced in 2000 and VW Touareg R5 2.5 UI produced in 2007) fuelled with diesel, rapeseed oil, chicken fat and rapeseed oil blended with ethanol. Performances and emissions were similar to those of diesel or FAME (Fatty Acid Methyl Ester). Emissions were measured at 60, 70 and 120 km/h always showing lower values than for diesel also and decreasing as the velocity increased. NOx emissions for vegetable oil were lower for each load condition; chicken fats NOx emissions were slightly higher than those for diesel.

Daho et al. [24] tested a 667 cm^3, low-pressure injection system ICE fuelled with cottonseed oil and cottonseed oil blended with diesel measuring specific fuel consumption, efficiency, exhaust gases temperature and emissions at different engine load. Results show that BSFC was 21% lower at full load (12% when referred to volumetric fuel consumption); CO emissions were higher, depending on load and oil blended, from 10% to 25.3% at low load and 100% of cottonseed oil fuelling; NOx were lower and this reduction was up to 9%.

Agarwal and Rajamanoharan [25] tested a 3.67 kW ICE fuelled with Karanja oil and Karanja oil blended with diesel measuring specific fuel consumption, efficiency, exhaust gases temperature, emissions and smoke opacity for different Brake Mean Effective Pressure (BMEP). For preheated blends and not preheated blends