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Research Article

Performance and Emissions of Sunflower, Rapeseed, and Cottonseed Oils as Fuels in an Agricultural Tractor Engine

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A comparative experimental investigation was conducted to evaluate the performance and exhaust emissions of an agricultural tractor engine when fueled with sunflower oil, rapeseed oil, and cottonseed oil and their blends with diesel fuel (20/80, 40/60 and 70/30 volumetrically). Tests were also carried out with diesel fuel to be used as a reference point. Engine power, torque, BSFC, thermal efficiency, NO_x and CO_2 were recorded for each tested fuel. All vegetable oils resulted in normal operation without problems during the short-term experiments. The 20/80 blends showed unstable results, in comparison to higher oil content fuels. Power, Torque and BSFC were higher as oil content was increased in the fuel. Rapeseed oil fuels showed increased power, torque and thermal efficiency with simultaneous lower BSFC in comparison to the other two vegetable oils. Cottonseed oil fuels gave better engine performance than sunflower oil fuels. In all oil types, NO_x emissions were augmented when fuel oil percentage was increased. Cottonseed oil fuels led to higher NO_x emission increase compared to rapeseed oil fuels. CO_2 emissions showed a tendency to be increased as the oil content was evolved. The highest CO_2 emissions were given by cottonseed oil fuels, followed by rapeseed and sunflower oil.

1. Introduction

Nowadays, agriculture has been developed as an economical sector where mechanization plays a significant role in the final output. However, over the last 40 years, the doctrine has been the maximization of production without taking into account the energy input and its environmental impact. It is evident that agricultural tractors have been widely used for all agricultural practices with important fuel consumption, due to high power needs during field operations.

According to European Energy Agency [1], agricultural sector stands for only 3.7% in EU energy profile. This percentage is low in comparison to other energy consumers. However, the fact that agricultural tractors count for 90–95% of total on field agricultural energy consumption [2] shows that total fossil fuel requirements for this purpose is significant. Therefore, measures on reducing fossil fuel consumption should be also adopted in this domain. To achieve such a goal, it is possible to optimize tractor engine performance or replace fossil fuel by an alternative fuel.

Ryan et al. [3] and Strayer et al. [4] stated that engine performance depends on the fuel used, the fuel injection, and the combustion characteristics. Engine manufacturers have improved diesel engines in terms of thermal efficiency (TE) by adopting several new technologies such as turbochargers, common rail system, multistage injection, and others. On the other hand, this engine performance increment in many cases caused a negative impact on emissions, and having in mind emission regulations, a solution could also be found in the application of alternative fuels of renewable nature, the so-called biofuels [5]. Biofuels have usually agricultural origin offering environmental benefits (i.e., exhaust emission reduction, nontoxicity) as well as decreasing countries' dependency on fossil fuels and improving agricultural income. The most common biofuels, which have already found their position in European fuel market, are bioethanol, vegetable oils, and their derived methyl esters (biodiesel). As agricultural tractors are powered by diesel engines, vegetable oils (VOs) that could be produced within the farm and used by agricultural tractors were only considered in this study.

VOs and diesel fuel (DF) have similar physical and chemical properties. When VOs are used as fuels on short-term tests, no problems are indicated, while on endurance tests a number of problems have been reported with injection coking (causing poor fuel atomization and dilution of the lubricating oil), cylinder deposits, ring sticking as well as solidification in cold operating temperatures [5–7]. The main reason for these drawbacks of VOs is viscosity that is up to 16 times higher than conventional DF. This parameter is crucial, because it causes larger VO droplets, which in combination with the higher distillation curves of VOs creates a slower evaporation process that considerably affects engine's combustion rate [5]. Therefore, it is essential to either change the engine characteristics to adapt with the new fuel type or to reduce viscosity. For instance, Higelin [8] interfered in the engine internal parts substituting the typical aluminum alloy piston of an agricultural tractor direct injection diesel engine (IDE) by an insulated piston with a stainless steel crown, which corresponded well in the combustion characteristics of pure sunflower oil. Nevertheless, most research has been directed to changing the fuel characteristics, which gives the advantage of not modifying existing engines. Consequently, different methods have been stated, such as fuel blending, fuel heating, esterification of vegetable oils, and thermal cracking [9, 10].

2. Literature Review

Fuel blending and heating have the advantage of nonindustrial intervention, which is ideal for rural, remote areas where the farmers do not have easy access to the market. Many researchers have worked in these methods with different VO types, with positive results. However, for the purposes of this study, a specific investigation in previous work related to three VOs [sunflower oil (SunO), rapeseed oil (RapO), and cottonseed oil (CotO)] was carried out.

Nwafor and Rice [11] tested RapO blends up to neat RapO in an IDE and concluded that all blends were acceptable in comparison to DF and the 50% blend gave the best results. In particular, BSFC was in the same level for all fuels; except in high load levels where neat RapO gave higher BSFC. Thermal efficiency (TE) was found to be better as oil content in the tested fuel was increased. Exhaust gas temperature followed the same trend as thermal efficiency and engine lubrication oil performed well, showing acceptable viscosity reduction. Unburned hydrocarbons were lessened when neat RapO was used. McDonnell et al. [12] used semirefined RapO blends up to 75% in an agricultural tractor direct injection diesel engine (DDE) and resulted that oil blends up to 25% were suitable alternative fuels. More specifically, as oil content in the fuel was increased, Power was reduced and BSFC was augmented, but according to the tractor operators, engine performance was not affected highly; while engine lubricating oil was slightly influenced from the fuel alteration and injector fouling was increased, but not quantified. Karaosmanoğlu et al. [13] completed a 50-hour endurance test of a DDE with SunO, and there were no significant changes in engine operation in comparison to DF. More precisely, there was no significant drop or increase of power or fuel consumption. The lubrication oil was not affected remarkably and injector nozzle was clean. Altin et al. [14] compared several preheated VOs in a DDE with minor power loss and emission increase. Between the tested VOs, SunO, CotO, and RapO were tested and rapeseed had better engine performance and cottonseed better emissions. The worst torque release was obtained with SunO and the best with RapO. The least power output was released with CotO, while the highest values were taken when RapO was used. SunO gave the highest BSFC. CO emissions were most increased with RapO, and CO_2 was higher with SunO, followed by RapO and CotO. NO_2 was lower with CotO, followed by SunO and RapO. Smoke level was the highest with RapO, followed by CotO and SunO. Rao and Mohan [15] investigated the effect of supercharging on a DDE performance with CotO and found that changes in injection pressure did not affect performance, but supercharging, even if low, provided better performance with BSFC reduction. Nwafor [16] examined fuel inlet temperature effect on RapO and resulted that fuel heating was beneficial at low speed and part-load operation. Particularly, RapO was selected to be preheated at 70°C according to laboratory tests, and it was seen that peak cylinder pressure was increased accompanied by a reduced delay period in comparison to unheated RapO. In addition, heat release was early like with DF, in contrast to unheated RapO where it is late. BSFC was increased with preheated RapO, compared to unheated RapO. In high loads, this increment was eliminated due to the fact that combustion temperature dominated the delivery rates and flow velocities in the fuel line and resulted in the same system temperature for both preheated and unheated RapO. Preheated RapO deteriorated TE compared to unheated RapO, explained by the higher viscosity of neat oil that acts like a lubricant and as a sealant between the piston rings and the cylinder wall. Ramadhas et al. [10] conducted a literature review about VO use in Compression Ignition (CI) engines and concluded that in technical terms it is important to carry out experimental work with different engine types and sizes to increase confidence in these fuels. He and Bao [17] used cottonseed oil blends in an agricultural diesel engine and preliminary testing revealed that 30% CotO had the best blend homogeneity (no sediment appearance). Therefore, they tried to optimize four parameters (intake valve closing angle, exhaust valve opening angle, fuel delivery angle, and injection pressure) to reach the highest TE. They came to the conclusion that fuel delivery angle was the most important factor and that 3–5°CA in advance would increase TE. Rakopoulos et al. [5] used 10 and 20% blends of CotO, SunO, soybean, corn, and olive kernel oil with DF in a DDE and resulted that low oil content biofuels could be used safely and advantageously in diesel engines. They found out that TE was maintained close to DF, with small BSFC increase. Smoke and CO were augmented as the oil content in the fuel was increased. NO_x emissions were reduced as fuel oil percentage was increased. Wang et al. [18] used VO/DF blends in a DDE and concluded that power and BSFC was almost the same with DF and NO_x, while CO and unburned hydrocarbons (HC) were lowered. Fontaras et al. [19] and Fontaras et al. [20] tested, respectively, 10% and 20% CotO/DF blends in

Table 1: Engine Specifications.

Make	Case New Holland
Type	Four Stroke direct injection diesel engine
No. of cylinders	4
Aspiration	Turbocharged
Cooling System	Water cooled
Stroke (mm)	132
Bore (mm)	104
Engine Capacity (cm^3)	4485
Compression Ratio	17.5
Type of fuel pump	RDP

a Euro 3 common rail DDE of a passenger vehicle, and there was no significant influence in either engine performance or emissions. The 10% CotO blend was found to cover all EN590 standard specifications, and it was used successfully on the car for 12000 km millage. Fuel consumption and CO_2 were fluctuating within the acceptable accuracy limits. NO_x were increased slightly in some cases, but never exceeded the Euro 3 emission limit.

In this study, a comparative study of SunO, RapO, and CotO was performed to observe a typical agricultural tractor engine behavior in terms of performance and emissions. The VOs were both preheated and blended with DF to minimize the high viscosity effect on engine operation. According to literature, a comparison of the selected VOs has not been executed on a total engine operation range and especially in an agricultural tractor engine. For Greek agriculture, it is also important to carry out testing of these VOs, which are major crops in the country and could be used for farm energy needs.

3. Materials and Methods

3.1. Experimental Apparatus

3.1.1. Engine Description. The engine selection was based on the average tractor engine power in Greek agriculture [21]. The engine used was a Case New Holland CNH 100A, four cylinder CI engine. It is a turbocharged, direct injection diesel engine with a rotational speed range of 700–2500 rpm. The injector nozzle sprays the fuel through 6 holes, forming a cone angle of 60°. The spraying starts when fuel line pressure reaches 250 bar. The rotary distribution principle (RDP) type "Bosch" fuel pump provides the fuel line with a pressure between 260 and 274 bar. The exhaust valve opens at 64°CA before top dead center (BTDC) and close at 26°CA after top dead center (ATDC), while the inlet valve opens at 10°CA BTDC and closes at 10°CA ATDC. The main specifications of the engine are illustrated in Table 1.

3.1.2. Test Rig Description. The experimental apparatus is shown in Figure 1. The engine was coupled on a Borghi and Saveri hydraulic dynamometer. The load on the dynamometer was measured by using a computer controlled strain gauge load sensor, which was calibrated using standard weights before the experiments. A proximity speed sensor was used to measure the speed of the engine, which was also calibrated by an optical tachometer.

The fuel consumption was measured using a burette with 100 mL volumes and a stopwatch. A conical funnel instrument was introduced just before the fuel tank. When the fuel volume of the burette was vacated into the funnel, the time measuring was started and when the 100 mL were consumed the measuring was terminated. This way, a rate of fuel consumption in relation to time was taken. The measurement was carried out three times. The throttle position was controlled by a mechanical actuator and it was stabilized in full throttle. Temperatures in all cylinders, inlet and outlet coolant, air filter, exhaust gas, air inlet manifold (after turbo charger), fuel line, and engine oil were recorded every second using a series of k-type thermocouples. Pressures in air inlet manifold, exhaust manifold, and fuel line were also recorded, using Gems, UK 2200 series high output pressure transducers. Finally, air flow before the air filter was being recorded using an insertion calorimetric sensor (FCS-GL1/2A2P-LIX-H1141/A, Turck, Germany). All temperature sensors were led to a temperature data logger (TC-08, Pico Technology, UK). All pressure and flow sensors were led to a general purpose voltage input data logger (ADC-24, Pico Technology, UK). Both data loggers were USB-connected to a PC, where data were stored. A new fuel tank was connected to the system for the alternative fuels.

Table 2: Accuracy of measurements.

Measurement	Unit	Measurements range	Accuracy
CO	%vol.	0–15	0.01
CO_2	%vol.	0–20	0.01
NO	ppm	0–5000	1
NO_2	ppm	0–1000	1
HC	ppm n-hexane	0–20000	1
O_2	%vol.	0–25	0.1

3.1.3. Exhaust Gas Analysis System. The exhaust gas analysis was consisted by a rigid emission gas analyzer (DELTA 1600L by MRU, Germany) that measures CO, CO_2, NO_x, HC, and O_2. The Nitrogen Oxides (NO and NO_2) were measured in parts per million (ppm), by volume with a chemiluminescent sensor. The CO and CO_2 (%) were determined by a Non-Dispersive Infrared Analyzer (NDIR) and the unburned HC in ppm, by volume with a Flame Ionization Detector Sensor (FID). The range and the accuracy of each measurement are given in Table 2.

3.1.4. External Fuel Preheating System. A VO preheating kit was installed for the preheating of the alternative fuels during the experimental work. A diagram of the kit is illustrated in Figure 2.

The manufacturer (W. Uhlig-U.T.G., Switzerland) provides this product for preheating pure VOs which are being used straight in the engine as fuels. In this work, it was used for preheating the selected VO/diesel blends, which was

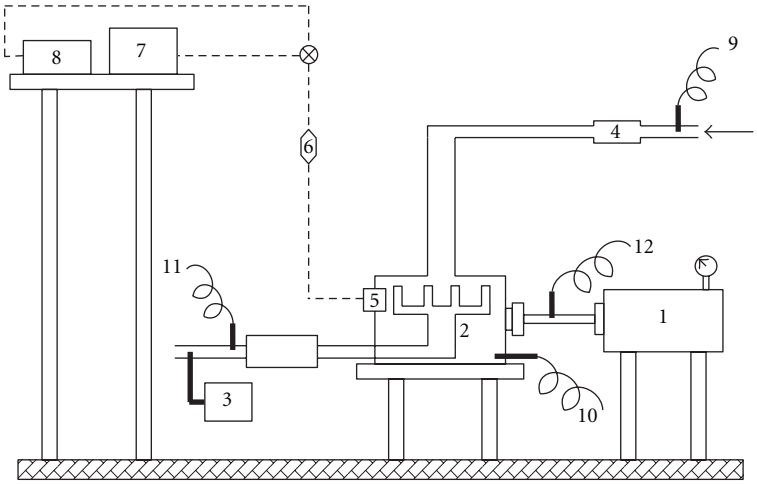

Figure 1: Experimental rig (1: Hydrokinetic Dynamometer, 2: Engine, 3: Gas Analyzer, 4: Air Filter, 5: Fuel Pump, 6: Burette, 7: Diesel Fuel Tank, 8: Alternative Fuel Tank, 9: Air Flow Meter, 10: Engine Oil Temperature, 11: Exhaust Gas Temperature, 12: Engine Speed Meter.

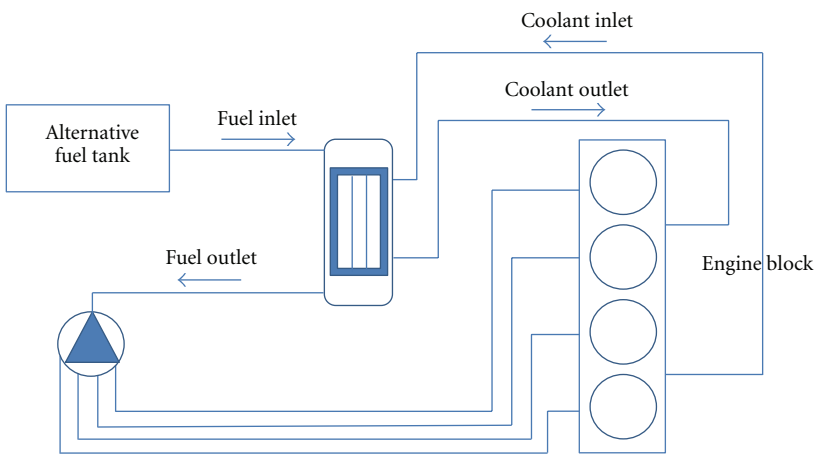

Figure 2: Preheating oil kit installed on the engine.

being carried out in a heat exchanger, through which engine coolant passes. At normal operation, the coolant temperature reached 85–92°C. The alternative fuel, passing through the heat exchanger received heat and extended its temperature in a range of 65–75°C, due to engine load change. Until the engine reached normal operating temperature, it run on conventional DF and the alternative fuel was not passing through the exchanger. When the coolant reached the above-mentioned fixed temperature, then with a three-way valve the fuel switched from DF to the selected alternative fuel.

3.1.5. Viscosity Measurements. Viscosity was measured using Ubbelohde type (Comecta type 0B, 1, 1C, and 2) glass viscometers. VOs and the VO/DF blends were prepared and oven preheated in temperatures ranged between ambient temperature (22°C) and 98°C. Eight measurements for each of the 13 alternative fuels were carried out with 10°C interval.

3.2. Experimental Procedure. The VOs used were all Greek originated, as the oil seeds were produced in three farms in Sterea Ellada Province, Greece, and were extracted on-site with the same procedure (screw expeller and filtration). Originally, the engine was run using DF and the results were used as reference point. Then, four (4) types of fuels for each VO were experimented; three VO/DF blends (20/80, 40/60, and 70/30 volumetrically) and 100% pure VO. The selection of blends was based on previous studies [11, 12, 17, 22, 23] and aimed on an overall blend range. DF was used in ambient temperature and only blends and pure VOs were first preheated. The blends were stirred well and the mixture remained always in a stable condition, which was shown by the fact that the blends remained stable after a 20-day idle in transparent tanks.

Initially, the engine was warmed until it reached operating temperature. The engine speed was then increased to maximum, which is 2300 rpm. The tests were performed according to OECD procedure [24] for tractor engines. Initially the maximum power is defined, which is usually detected by small changes around the given manufacturer maximum power engine speed. Then, five part load tests follow.

Table 3: Physical and chemical properties of the three vegetable oils and diesel fuel.

Fuel Type		Diesel	Sunflower oil	Rapeseed oil	Cottonseed oil
Acronym		DF	SunO	RapO	CotO
Calorific value	MJ/kg	43.350 [10]	39.525 [10]	37.620 [10]	39.648 [10]
Viscosity at 35°C	cSt	3.05 (measured)	40.96 (measured)	42.38 (measured)	41.67 (measured)
Density at 25°C	kg/m^3	815 [10]	918 [10]	914 [10]	912 [10]
Carbon residue	%	Max 0.4 [25]	0.13 [26]	0.3 [25]	0.23–0.25 [27]
Ash content	%	Max 0.01 [25]	<0.01 [26]	0.003 [25]	0.02 [28]
Cetane number	—	47 [10]	37.1 [10]	37.6 [10]	48.1 [10]
Iodine value	cg I.g oil	95–125 [25]	126.3 [29]	112 [25]	103–115 [30]
Saponification value	mgKOH/g oil	— [29]	191 [29]	197.07 [28]	207.71 [28]
Sulphur content	%	0.27 [12]	0.01 [28]	0.00 [12]	0.008–0.010 [27]
Water content	%	<0.1 [31]	<0.1 [31]	0.06 [25]	—
Carbon content	%	87.5 [31]	77.6 [31]	—	—
Flame point	°C	58 [14]	220 [14]	275–290 [14]	210 [14]
Flash point	°C	76 [32]	274 [32]	246 [32]	234 [32]
Cloud point	°C	−2.2 [13]	7.2 [32]	−3.9 [32]	1.7 [32]
Pour point	°C	−12.2 [13]	−15 [32]	−31.7 [32]	−15 [32]
CFPP	°C	−10.1 [13]	−18 [13]	−15 [13]	−6 [33]
Chemical formula	—	$C_{16}H_{34}$ [14]	$C_{57}H_{103}O_6$ [14]	$C_{57}H_{105}O_6$ [14]	$C_{55}H_{102}O_6$ [14]

The first test is taken at the torque corresponding to maximum power, the second with 85% of the torque defined in the first test, the third with 75% of the second test torque, the fourth with 50% of the second test torque, and the fifth with 25% of the second test torque. In this study, the procedure of the code was followed, with an exception of the last mentioned test that was not carried out, because the dynamometer had a very large torque range and it could not reach such a low point. In order to cover the whole engine load range, two more part load tests were added that resulted in eight comparable points of the engine operation range. In every load test, power, torque, fuel consumption, engine temperatures and pressures, air flow, and gas emissions were measured. Atmospheric pressure and air temperature were also recorded, and measured torque was corrected according to them. At each point, the engine was stabilized for three minutes and then the measurements were taken. Three measurements of all parameters, per minute, were recorded for every test, for eliminating statistical errors. The warming-up of the engine in all the experiments was conducted using DF. After warming-up, the alternative fuel was used and in the end of the experimental procedure the fuel was again switched to DF, in order to flush out the fuel lines, the injection pump and the injectors before shutting down.

Finally, the results from the tests were statistically analyzed. They were compared using pair t-tests with 95% confidence interval. The statistical analysis was carried out with the SPSS Release 16 (SPSS Inc., 2007).

4. Results and Discussion

4.1. Fuel Properties. The main properties of the three tested VOs and DF are shown in Table 3. VOs exhibit high values of viscosity that could be reduced by preheating or blending with DF as stated above. In this study, viscosity testing was conducted for all 13 tested fuels to comprehend the effect of high temperature and mixing with DF on the final fuel viscosity. The results are illustrated in Figure 3.

Table 4: Engine performance parameters with diesel fuel (reference fuel).

Parameter	Engine speed (rpm)	Load (%)	Value
Max Power (kW)	2198	69.75	64.1
Max Torque (Nm)	1280	100	399.2
Max Thermal Efficiency (%)	1574	90.1	36.45
Min BSFC (g/kWh)	1574	90.1	228.5

The temperature range under consideration was 65–75°C, which was the fuel inlet temperature after passing from the preheating device. Hence, in comparison to DF in ambient temperature (23°C), the preheated (65–75°C) 20/80 blends showed lower viscosity values (30–40%) and the 40/60 blends had viscosity values ranging between −5 and +10%. The 70/30 blends had 60–120% higher viscosity and the pure VOs 200–340% higher values than DF. From Figure 3, it is obvious that the three VOs followed the same trend as the blend oil content and temperature increase.

4.2. Engine Performance. In order to evaluate the alternative fuels in terms of engine performance, a comparison of the 13 fuels under investigation was conducted, in terms of power and torque output, BSFC and total TE. The measured values for these parameters using DF as the reference point are illustrated in Table 4.

In the comparison of the engine performance parameters, which is illustrated in the following Figures 4–8, every parameter is shown as a difference percentage from the respective DF reference value.

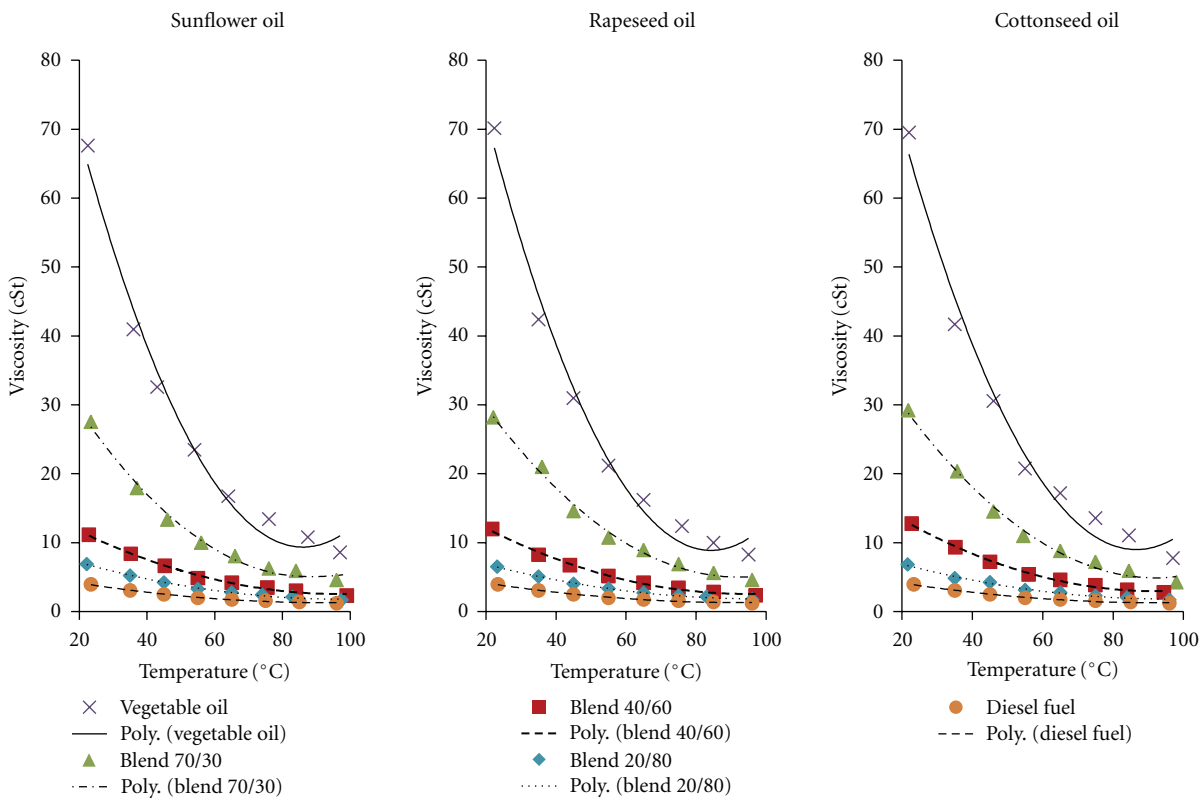

Figure 3: Viscosity measurements for diesel and the three oil types.

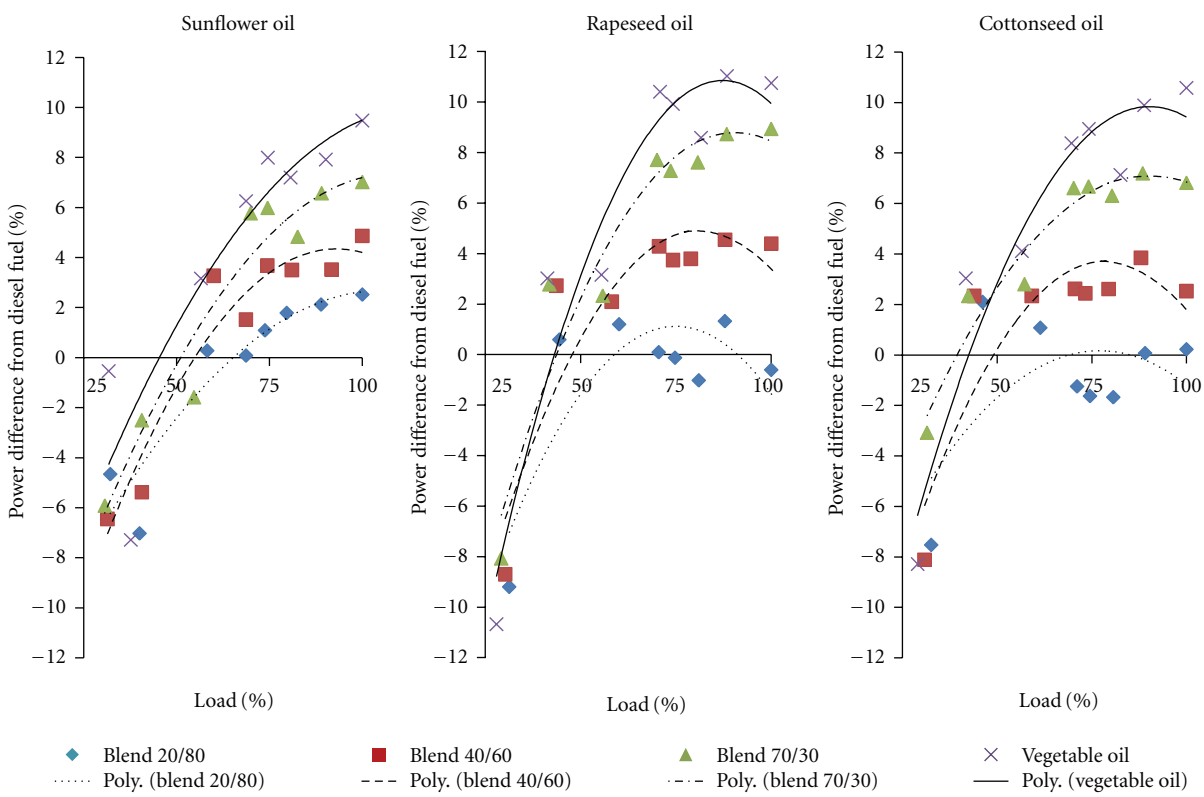

Figure 4: Comparison of Power output between diesel fuel and the three oil types.

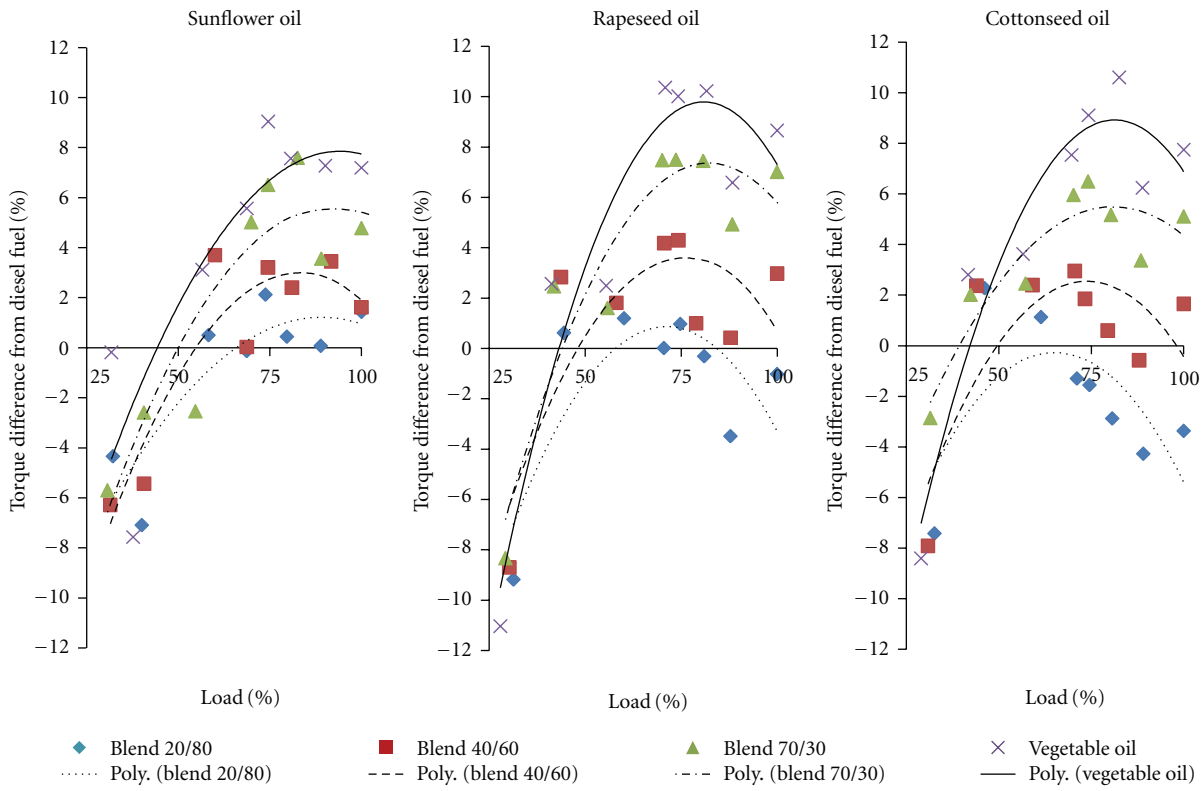

Figure 5: Comparison of Torque output between diesel fuel and the three oil types.

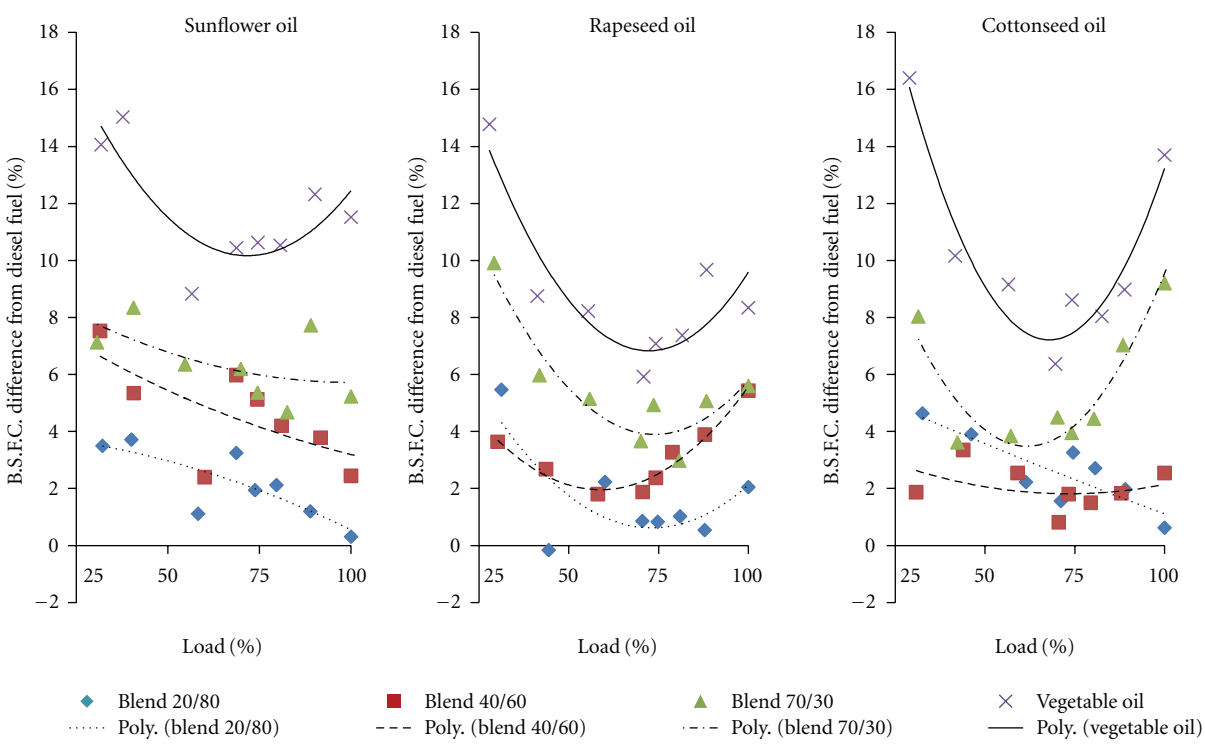

Figure 6: Comparison of B.S.F.C. between diesel fuel and the three oil types.

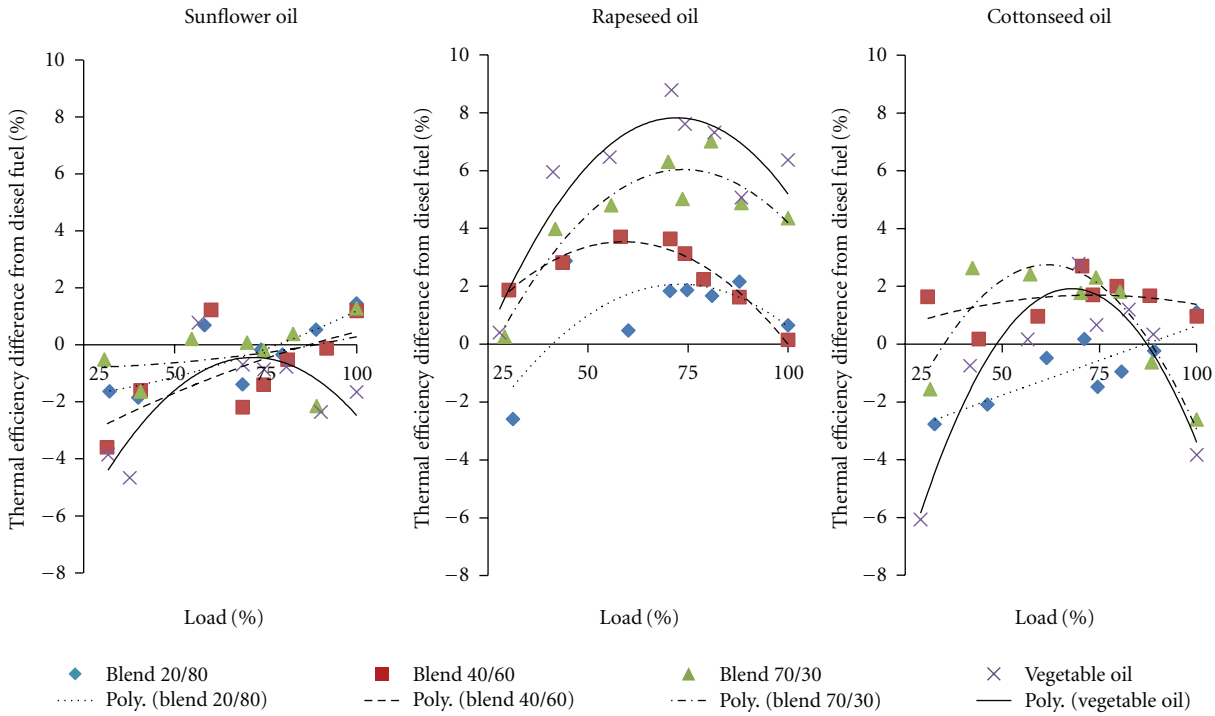

Figure 7: Comparison of thermal efficiency between diesel fuel and the three oil types.

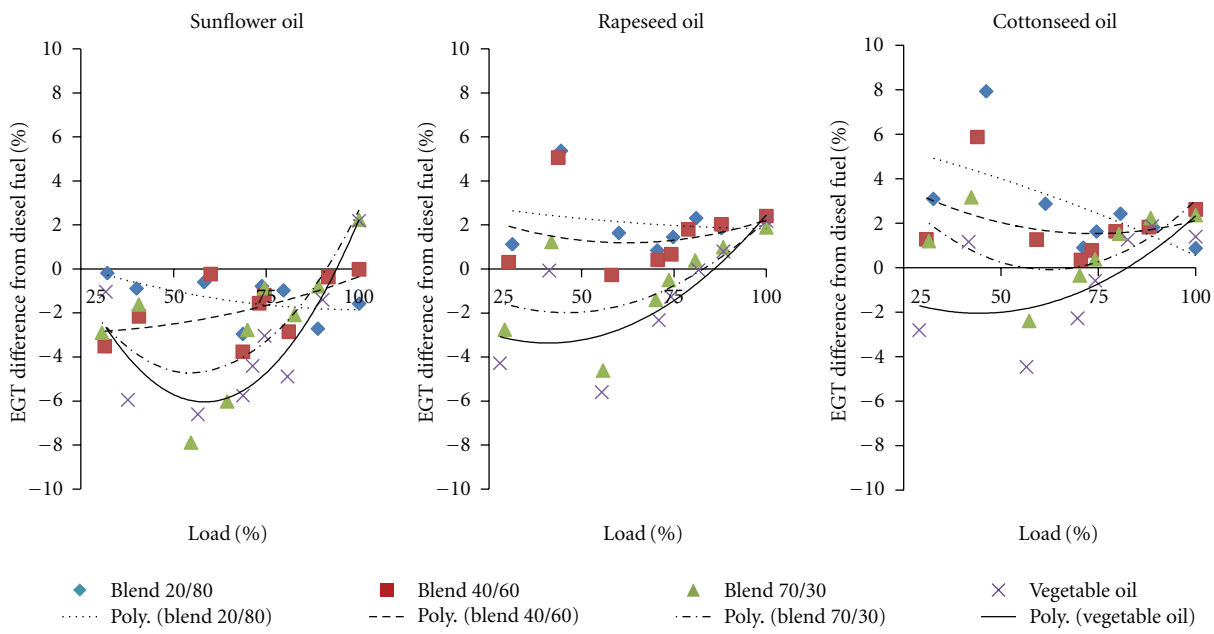

Figure 8: Comparison of exhaust gas temperature between diesel fuel and the three oil types.

4.2.1. Power and Torque. The variations in power and torque of the engine with the VOs are presented in Figures 4 and 5, respectively. In high loads, all VOs followed the same trend of increased power and torque outcome as the oil content was increased.

However, in low loads, engine power and torque release were higher using DF. This phenomenon could be explained by the fact that in high load setting, the engine speed was low and the VO had more time to complete its combustion, as it always has a higher ignition delay and combustion rate [5]. In addition, it is possible that the combustion process was perhaps changed from evaporation controlled to mixing controlled as the load increased [34].

Comparing the three VOs, it was observed that RapO presented the highest power and torque difference than DF (11%), in comparison to CotO (10.6%) and SunO (9.5%).

The 70/30 blends followed the same trend as the pure VOs. Nevertheless, with lower oil content the engine seemed to behave better with SunO. It was seen that SunO40 gave the same increase as RapO40 and CotO40 was listed third. The SunO20 was the only 20/80 blend to show natural continuation to the previous blends, when the other two gave scattered results with lower power and torque output in general. This was not expected, as the blending was made following the same procedure. Finally, it should be mentioned that only SunO based fuels showed a continuous increment until the maximum load.

4.2.2. Brake Specific Fuel Consumption. Figure 6 illustrates that all blends and pure VOs showed increased BSFC in comparison to DF. It is also demonstrated that as oil content was increasing, BSFC was also increased. This trend could be explained by the higher density of all VOs, which leads to increased gravimetric fuel consumption due to increased fuel mass for the same volume of fuel injected by the fuel pump. In addition, lower calorific value might also increase the volumetric fuel consumption to keep similar energy input to the engine [23, 35]. In addition, as the engine load increases, BSFC decreases [19, 35]. In this study, this trend was observed for all fuels. Between the three VOs, statistical significant differences were observed for the 40/60 blends and pure VOs. In the case of agricultural tractors, the engine runs in the range of 60–80% load, where most of agricultural practices are taking place. Therefore, it is positive that Figure 6 shows the least BSFC increase in appraisal to DF obtained within this specific range.

4.2.3. Thermal Efficiency. Figure 7 illustrates the Thermal Efficiency (TE) difference of the VOs from DF. Each of the VOs showed completely different output. RapO fuels have exhibited the best TE result, as power increase was considerably higher than the respective BSFC raise. In particular, the oil content of the fuel played a positive role in the final TE, with pure RapO indicating maximum increase of 8.4%. from Apart RapO20, all RO fuels were statistically significantly different than DF (average TE increment: RapO 5.9%, RapO70 4%, RapO40 2.5%). The situation was altered significantly with SunO and CotO fuels, which generally presented lower TE, and there were no indication of oil content influence in TE. In general, CotO and SunO fuels did not show statistical differences from DF, except CotO40 (TE average increment of 1.1%). Comparing the three VOs, RapO fuels were better than the other two VOs with statistical differences. According to these results, RapO seems to provide better combustion process, even if oil properties and viscosity in particular are in the same level as the other VOs. This could be explained as combustion is always enhanced by high air/fuel (A/F) mixture, good atomization, and spray characteristics [23]. Unsaturated oils enhance mixing, due to their loose bonds between the molecules [36]. Table 5 [37] displays the free fatty acid contents of the three tested VOs, and it can be seen that RapO contains the highest percentage of unsaturated fatty acids.

Table 5: FFAs content of the three tested oils [36].

	Saturated (%)	Monounsaturated (%)	Polyunsaturated (%)
Sunflower oil	11.9	20.2	63.0
Rapeseed oil	5.3	64.3	24.8
Cottonseed oil	25.5	21.3	48.1

In addition, RapO has a lot of monounsaturated fatty acids, which gave an indication that these acids promote more air/fuel mixing.

4.2.4. Exhaust Gas Temperature. Engine exhaust gas temperature using as fuel the three VOs in comparison to DF is presented in Figure 8.

It is evident that this factor was not significantly changed in comparison to DF. The exhaust gas temperature (EGT) of CotO fuels is higher than the respective SunO and RapO fuels, as it is evident that highly polyunsaturated fatty acid oils exhibit higher ignition delay and shorter premixed combustion periods, which means that the after burning period is extended and the final temperature of the exhaust gases is higher [36, 38].

4.3. Engine Emissions. Investigation of performance characteristics has to be combined with engine emissions examination, in order to have an overall view of VOs as fuel in comparison to DF. The gas analyzer available had the capability of measuring unburned HC, CO, O_2, CO_2, and NO_x (NO, NO_2) and all of them were logged during the experiments.

However, HC and CO values were very low and according to the instrument accuracy (Table 2), they cannot be considered as reliable. More precisely, unburned HC were always between 0 and 5 pmm, while CO was measured in %, which was not accurate enough to show the low CO values obtained from the measurements (the figures were always between 0.01 and 0.03%). Hence, HC and CO were not taken into account in the analysis below. In both cases, it should be stated that in absolute terms these emissions are of no real concern [5].

4.3.1. Nitrogen Oxides (NO_x). Figure 9 presents the difference of NO_x emissions between the 12 alternative fuels and conventional DF. It can be observed that the use of VO had a significant influence in the NO_x emission level. It has to be pointed out that the main factor to receive increased NO_x emissions is the elevated cylinder temperature [32, 35].

In addition, according to Rakopoulos et al. [5], fuels with high cetane number (DF in this case) were expected to produce lower NO_x levels, due to lower ignition delay that creates shorter premixed combustion, which is the main phase of NO_x production. Moreover, the fact that the engine under testing exhibits a very high A/F ratio added to NO_x increment, due to the O_2 excess available for chemical reaction with the atmospheric N. In addition, O_2 is contained in the VO molecule and this resulted in higher NO_x emissions. As the oil percentage was increased, NO_x emissions were

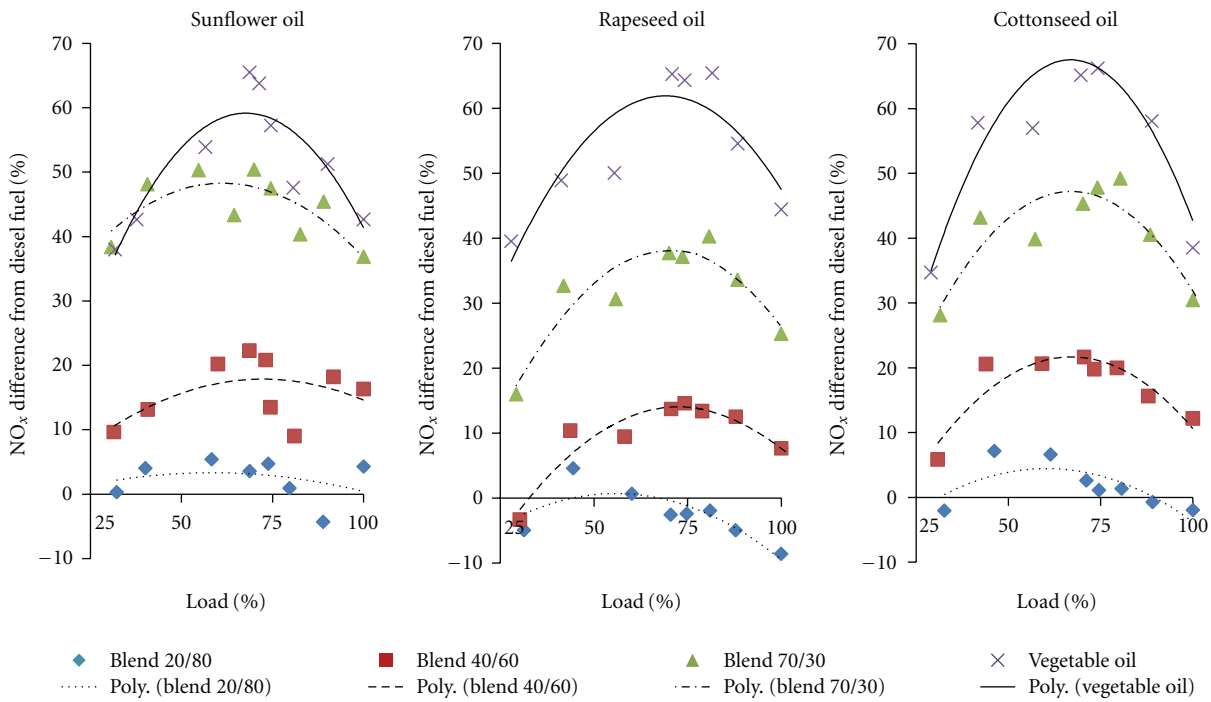

Figure 9: Comparison of NO_x between diesel fuel and the three oil types.

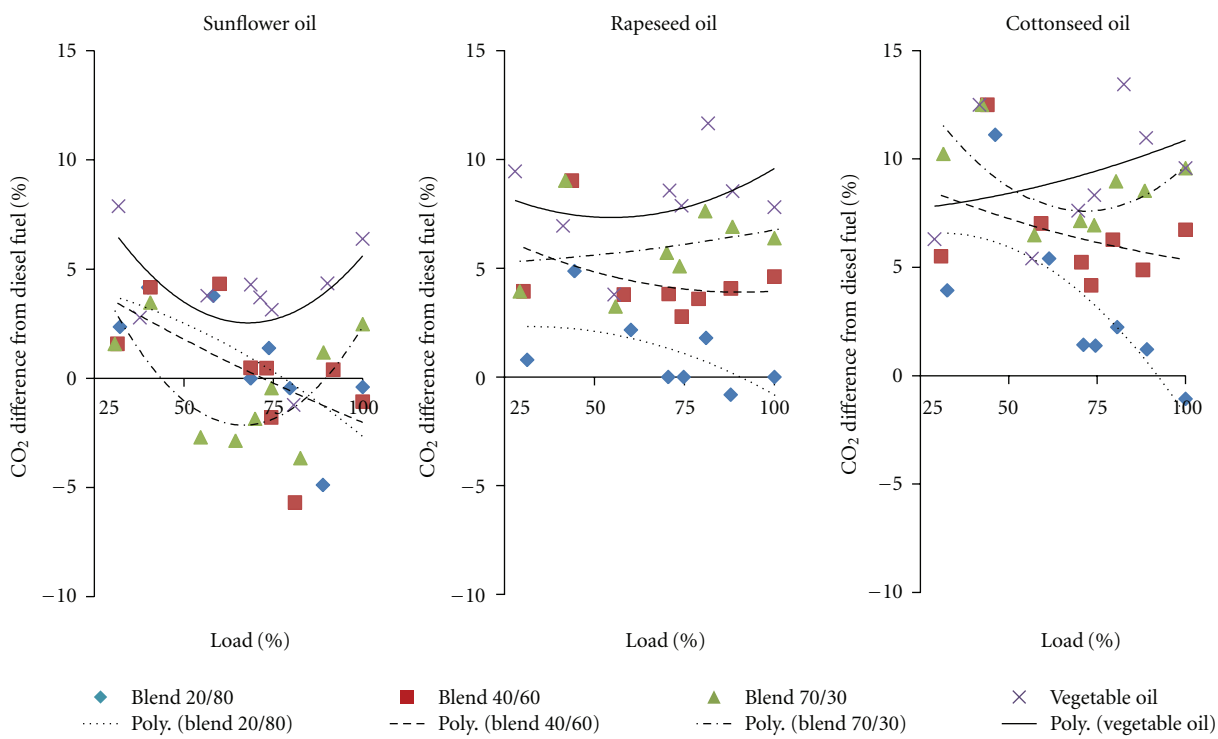

Figure 10: Comparison of CO_2 emission between diesel fuel and the three oil types.

augmented and the effect was similar for the three VOs. However, there was a noticeable phenomenon in the case of 20/80 blends; where all VOs gave positive and negative results with no statistical differences. It seems that in these blends the combination of DF and VO reduced the combustion temperature and reduced NO_x levels. This might happen due to bad fuel mixture with the air that led to incomplete combustion of lower temperature [5].

A general observation of Figure 9 illustrates that RapO fuels had the best behavior in terms of NO_x emissions. More specifically, RapO20, RapO40, and RapO70 produced statistically the least NO_x emissions, leaving the respective CotO

fuels second and SunO fuels last. In the case of pure VOs, there were no statistically significant differences.

4.3.2. Carbon Dioxide (CO_2). Figure 10 presents the CO_2 emissions produced by the VO fuels in comparison to DF. In general, with exception in RapO20 and CotO20, CO_2 emissions were increased compared to DF. This is an indication of better combustion, due to oxygen content of VOs. It can be seen that high oil content increases CO_2 levels. A tendency of lower CO_2 values of SunO fuels is illustrated, leaving RapO fuels in the second place and CotO fuels last. This fact could be explained by better combustion characteristics of CotO, giving a less incomplete combustion.

5. Conclusions

An experimental investigation was conducted to evaluate the performance and exhaust emissions of three Vegetable oils [Sunflower Oil (SunO), Rapeseed Oil (RapO), and Cottonseed Oil (CotO)] and their blends with Diesel Fuel (DF) and compare the results with the reference fuel (DF). The work was conducted in a fully instrumented direct injection agricultural tractor engine. The conclusions extracted in terms of engine performance and exhaust emissions were as follows.

(i) All vegetable oil fuels provided as fuels to the engine had resulted in normal operation without problems during the short-term experiments.

(ii) The 20/80 blends showed unstable results with unclear trends, in comparison to higher oil content fuels.

(iii) Power, Torque, and BSFC were higher as oil content was increased in the tested fuel.

(iv) RapO-based fuels gave the best results in terms of Power and Torque increment with a simultaneous lower BSFC increase. As a result, engine thermal efficiency was significantly better than when using the other vegetable oils. CotO fuels were on average better than SunO fuels.

(v) NO_x emissions were augmented as oil percentage in the fuel was increased.

(vi) RapO fuels increased the NO_x production less than CotO fuels, leaving SunO fuels last.

(vii) CO_2 emissions showed an increase tendency as the oil content was evolved when RapO and CotO fuels were used. SunO fuels gave blurred results on this issue.

(viii) The highest CO_2 emissions were produced when CotO fuels were tested, followed by RapO and SunO fuels.

As a main conclusion, the use of RapO illustrated better behavior as alternative fuel to DF in the direct injection agricultural tractor engine of this study.

Nomenclature

ATDC: After top dead centre
BTDC: Before top dead centre
BSFC: Brake specific fuel consumption
CA: Crank angle
CI: Compression ignition
CO_2: Carbon dioxide
CO: Carbon monoxide
CotO: Cottonseed oil
DDE: Direct injection diesel engine
DF: Diesel fuel
HC: Hydrocarbons
IDE: Indirect injection diesel engine
NO_x: Nitrogen oxides
RapO: Rapeseed oil
RDP: Rotary distribution principle
SunO: Sunflower oil
TE: Thermal efficiency
VO: Vegetable oil.

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