Emission characteristics of a compression ignition engine running castor biodiesel as a blending agent

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Abstract: The objective of this study was to investigate the effects of castor biodiesel and its blends on the emission characteristics of a compression ignition engine. The research work was carried out on a single cylinder, four-stroke, water cooled, direct injection diesel engine by using biodiesel made from castor oil, compared with conventional diesel. The fuels used in the analyses are B5, B10, B15, B20, B25, B50, B100 and convectional diesel. The compression ignition engine was operated by varying the loading conditions (0 - 6 kW) in a step of 1 kW. Based on the parameters measured, detailed analyses were carried out on five regulated exhaust emissions i.e. NO_X, CO, CO_2, O_2, and HC. The results clearly indicated that the engine running with biodiesel and their blends were reduced in CO, CO_2 and HC emission by up to 20%. However, further reductions in emissions (CO, CO_2, and HC) were observed as biodiesel concentration increases in the blends. Also, for biodiesel and its blends, the NO_X (10.6% - 37.7%) emissions increased with increase in the load and, directly proportional to biodiesel concentration while O_2 reduces as the load increases and increases as biodiesel concentration increased. The results from the experiments suggested castor biodiesel oil with the engine exhaust gases could be a good substitute fuel for existing diesel engine

Keywords: compression ignition engine, castor biodiesel, exhaust, emission, nitrogen oxides, oxygen and carbon monoxide

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1 Introduction

Biodiesel is a chemically modified alternative fuel for use in diesel engines without major modifications. It is obtained from vegetable oils and animal fats and it is produced at a commercial scale by the transesterification of vegetable oils with methanol or ethanol. The direct use of alcohol as fuel causes several performance and corrosion problems which can be solved through transesterification. The given biodiesel contributes to reducing greenhouse effect gas emissions when compared to conventional diesel (Ali and Hanna, 1994; Chang *et al*., 1996; McDonnell *et al*., 1999; Peterson and Reece, 1996; Scharmer, 1998).

Many researchers have shown that biodiesel is one of the most promising alternative and environmentally friendly fuels which could be used in compression ignition engines, with little or no requirement of engine hardware modifications (Ramadhas et al., 2005; Hammond et al., 2008; Lapuerta et al., 2005; Durbin et al., 2000; Puppan, 2008). It has also been shown that biodiesel has significant potential to reduce CO_2, CO, HC and PM emissions

Lapuerta et al. (2005) and Xue et al. (2011) reported that 85% and 65% respectively of researchers agreed that

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the NO_x emission of an engine fuelled with biodiesel was higher than that of engines running with conventional diesel. One of the fundamental reasons behind this observation is the early initiation of engine combustion when running with biodiesel as a result of the advanced injection derived from the physical properties of biodiesel such as viscosity, density, compressibility and speed of sound (Cardone et al., 2002). Just a few numbers of researchers have reported that the NO_x emissions were reduced when biodiesel was used as a fuel (Dorado et al., 2003; Utlu and Koçak, 2008; Qi et al., 2009; Armas et al., 2010). The main reason for NO_x reduction is due to higher degrees of saturation, the longer chain lengths and higher cetane numbers of fuel from vegetable oils (Pala-En et al., 2013). Lapuerta et al. (2005) and Xue et al. (2011) also reported that 90% and 84% respectively of the papers reviewed show decreases in CO emissions when the engines were run with biodiesel fuel. The researchers explained that the main reason for the reduction of CO emission is due to the extra oxygen content of biodiesel which enhances the complete combustion and leads to the reduction in CO emissions (Tesfa et al., 2014). CO_2 is one of the gases emitted during combustion of carbon in the fuel. Xue et al. (2011) have reported that 46% of the researchers have reported that CO_2 emission increases when the engine is running with biodiesel, while 38.5% of the researchers reported the reverse trend, and 15.4% of the researchers reported that engines running with diesel and biodiesel have similar emissions. The CO_2 trend discrepancy may be happening due to the variation of biodiesel feedstock sources, engine types and testing procedures (Pala-En et al., 2013). The research specifically addressed the implication and anticipated environmental impact of using the selected engine cylinder types that would be the eventual target of application of this biodiesel. The information is significant and not currently available. The use of biodiesel as substitute for diesel is a clear indication and confirmation for reduction in dependency on mineral fuel. The utilization of diesel engine is indispensable, there could be seemingly decrease in its production. The main objective of this study was to investigate the effects of castor biodiesel and its blends on the emission characteristics of a compression ignition engine.

2 Experimental facilities and test procedures

In this study, the combustion characteristics of a compression ignition engine running with biodiesel produced (B5, B10, B15, B20, 25, B50 and B100) were investigated using a single cylinder, four-stroke, water-cooled and direct-injection internal combustion engine. This engine was selected due to its wide ranges of usage for powering stationary agricultural machine in Nigeria. A schematic of the experimental facilities is shown in Figure 1, and the details of the engine specifications are presented in Table 1. The engine was connected to dynamometer (Model: DG-1, MegaTech. Corperation) for measuring the power output and alternator (for varying the loads on the testing engine). The measurements of gaseous emissions were carried out with an exhaust gas analyzer (ALTAIR 5X MultiGas Detector). The measuring ranges are presented in Table 2. The gas analyzer probe was connected directly to the exhaust pipe and the insulated line is extended from the exhaust pipe to the equipment units where the analyzers are located. During the testing, the engine was run for five minutes to enable it to come to a steady state before any measurements were recorded. The maximum rated speed and maximum power of the test engine were specified to be 850 rpm and 8 Hp. (6 kW) respectively. The tests were carried out for a range of loads; from no load to maximum load (0 to 6 kW) with a step of 1 kW. Tables 3 and 4 presents the specifications of other instruments used and exhaust gas analyzer measuring ranges. The oil extracted from castor bean seeds and converted into fuel through a transesterification process using methanol and KOH as a catalyst. To analyze the dependence of fuel blends on the emissions of engines, castor biodiesel, and conventional diesel were used. The blended fuels were prepared by mixing castor biodiesel and diesel fuel in different proportions with percentage volumetric fraction of 5%, 10%, 15%, 20%, 25% 50% and 100% of Biodiesel and named B5, B10, B15, B20, B25, B50 and B100 respectively. The blend ratios were set to cover the full possible range of biodiesel application in emission reduction.

2.1 Load panel

The loading panel (used for varying the load on test rig) was made of plywood of 100 cm width and 120 cm height. This load panel consists of thirty bulbs of 200 W each which was connected in series, with one switch controlling five bulbs. The loads were varied from 0 kW to 6 kW in step of 1 kW at the rated speed of 1500 rpm

2.2 Alternator

A shunt D.C electrical alternator was used for the experiment while varying the loads on the engine and the bulbs were connected in series the circuit to control the load precisely by controlling voltage. The specifications of the electrical generator are shown in Table 3 and Table 4 presents the specifications of other instruments used.

2.3 Physical properties of castor biodiesel

Suitability of castor biodiesel blends was analyzed, and it was observed that the main physical properties of castor biodiesel (B5 – B25) satisfied the standard specifications (ASTM D-6751, EN-14214, and IS-15607). Density, calorific value, and viscosity of the castor biodiesel were measured. The blends physical properties are presented in Table 5. The density obtained for castor biodiesel is close to the previous work carried out on the same seeds by Asmare and Gabbiye (2014) whose result was 920 g cm^{-3}.

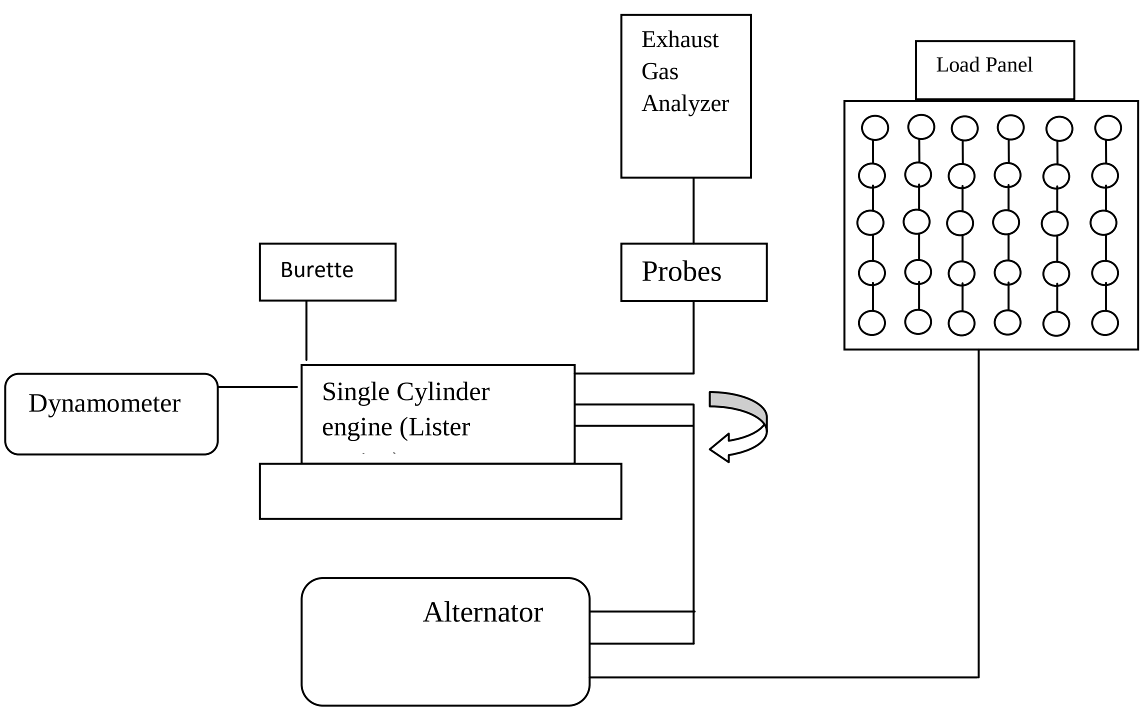

Figure 1 Schematic diagram of experimental set-up

A similar trend was observed by Raheman and Ghadge (2007) they found out that the density of crude mahua oil was reduced by about 9% on its conversion to biodiesel. The densities were observed to increase linearly with the increasing concentration of biodiesel in the blends. Calorific value of castor biodiesel is less (38,470 kJ kg-1) as compare to petroleum diesel (42,000 kJ kg-1). The decrease in calorific value will lead to higher consumption of fuel from the biodiesel-diesel blend and raw biodiesel as compared to diesel. Castor Biodiesel is more viscous (10.9 mm2 s-1) as compared to diesel (2.3 mm2 s-1). It is clear from the table that kinematic viscosity of different biodiesel blend increases with an increase in biodiesel concentration and vice versa. However, Aydin and Bayindir (2010) and

Utlu and Koçak (2008) submit that higher viscosity results in the power losses, because the high viscosity decreases combustion efficiency due to bad fuel injection atomization.

Table 1 Engine technical specification

Item	Technical data
Model	JUMBO stationary diesel engine
Type	4 stroke, vertical and cold starting totally enclosed
Horsepower	8
Bore (mm) × Stroke (mm)	114.3 × 139.7
Rotation	Clockwise
Combustion principle	Compression ignition
Cubic capacity (CC)	1432.71
Rated RPM	850 rpm
Fly wheel dia. (mm)	590
Fly wheel width (mm)	90
No. of cylinder	One
Method of cooling	Water
Starting	Hand start with a cranking handle
Bearing	taper roller bearings
Lubrication system	splash lubrication system

Table 2 The exhaust gas analyzer measuring ranges

Emission	Measuring range
CO	0-2000 ppm
O_2	0-30%
NO	0-250 ppm
HC	0-100 ppm
CO_2	0-100%

Table 3 Alternator specifications

Particular	Specifications
Model	Delmax
Phase	Single
Output	7.5 Kva
Volt	230
RPM	1500
Frequency	50HZ
Type of Cooling	Fan cooled

Table 4: Specifications of instruments

S/N	Particular	Specifications
1.	Speed measurement	Mechanical Tachometer Analogue handheld Tachometer Model: LZ-30 Range: 30-12000 rpm
2.	Fuel measurement	Burette and stopwatch
3.	Exhaust gas analyzer	ALTAIR 5X Multi Gas Detectors

Table 5 Physical properties of castor biodiesel

Sample	B100	B50	B25	B20	B15	B10	B5
Density, g cm^{-3}	953.63	908.77	880.52	875.76	871.96	869.79	865.38
Kinematic Viscosity, $mm^2 s^{-1}$	10.9	6.5	4.79	4.76	4.73	4.64	4.5
Calorific value, kJ Kg^{-1}	38,470	39,500	40,200	41,230	41,410	41,620	41,800

3 Emission analysis

Compression ignition engine emission was measured with exhaust gas analyzer (for CO, NO_X, CO_2, HC, and O_2) and the measured emissions were presented in Figures 1-5.

3.1 HC emission

HC exhaust emissions are shown in the Figure 2. For all loading conditions and blends of castor biodiesel, the HC emissions were less than that of the conventional diesel and HC emissions found to increase with the increase in loads and reduce as castor biodiesel concentration increases. This result is confirmed by the work of Lin et al. (2009) reported that the HC emissions reduced in the range of 22.47%-33.15% for the 8 kinds of biodiesels. Tan et al. (2012) found that when biodiesel was compared with the petroleum diesel fuel, the HC emissions show continuous reductions with increasing biodiesel blends at the 0.10 MPa, 0.26 MPa, 0.51 MPa and 0.77 MPa engine loads. Also, a good number of researchers reported a sharp decrease in Hydrocarbon emissions when substituting conventional diesel fuel with biodiesel fuels (Pinto et al., 2005; Monyem and Van Gerpen, 2001; Schmidt and Van Gerpen, 1996; Masjuki et al., 1993). It is important to note that few studies from available literature revealed that there are no significant differences when biodiesel is used as a replacement for conventional diesel fuel (Labeckas and Slavinskas, 2006; Yuan et al., 2005; Aakko et al., 2002). Several propositions were put forward to explain the decrease in hydrocarbon emissions when substituting conventional diesel for biodiesel – that biodiesel contains oxygen in its structure, thus, when added to petroleum-based diesel, the oxygen content of blended fuel increases, but little oxygen is needed for combustion. Increased oxygen content in the fuel is probably the reason for better combustion and reduction in HC emission (Pinto et al., 2005). Rakopoulos et al. (2004) report in their findings that hydrocarbon emissions decrease as the oxygen in the combustion chamber increases, either with oxygenated fuels or oxygen-enriched air. The higher cetane number of biodiesels reduces the combustion delay, and such a reduction has been related to decreasing hydrocarbon emissions (Monyem and Van Gerpen, 2001; Abd-Alla et al., 2001).

3.2 CO_2 emission

The carbon dioxide emission from single cylinder compression ignition engine using conventional diesel, biodiesel, and its blends are shown in Figure 3. The CO_2 emissions increased with increase in loads and decreased as biodiesel concentrations increased, given all loading conditions. Thus, the Figure 3 shows that CO_2 emission for the diesel is higher than that of any blend of the biodiesel. This is due to fact that diesel contains higher carbon content quantity in comparison to biodiesel. The increase of CO_2 emission at higher loads was due to higher exhaust gas temperature and lower O_2 concentration in the exhaust, which led to complete combustion (Jafarmadar and Pashae, 2013). Similarly, Mohsin et al. (2014) reported that the reduction in CO_2 emission from the engine was due to complete combustion inside the combustion chamber. More CO_2 released means complete fuel combustions. Although CO_2 is considered as a pollutant from the engine performance point of view, this is an indication that the engine will perform well and release less pollutant into the atmosphere with biodiesel. Also some other literatures studied CO_2 emissions of biodiesel and reported that, biodiesel results in fewer CO_2 emissions than diesel during combustion due to the lower carbon to hydrogen ratio (Ozsezen et al., 2009; Utlu and Kocak, 2008; Keskin et al., 2008; Lin and Lin, 2007; Sahoo et al., 2007). On the contrary, Çelikten et al. (2012) noted that the CO_2 emissions for biodiesel blends increased compared to diesel fuel. They attributed the increase to the oxygen content in biodiesel which reacted with unburned carbon atoms during the combustion and increased the formation of CO_2. Therefore, more amount of CO_2 in exhaust emission indicates complete combustion of fuel compared to diesel fuel. Similarly, other literatures reported that CO_2 emissions rise, or increase is due to more efficient combustion. They pointed out that, the higher carbon dioxide emission should cause less concern because of Nature’s recovery by raising biodiesel crops (Fontaras et al., 2009; Labeckas and Slavinskas, 2006; Canakci, 2005; Puhan et al., 2005; Ramadhas et al., 2005).

3.3 NO_X emission

Variation of NO_X produced by the engine used for the experimental work (stationary, single cylinder lister engine of 6 kW) when B5, B10, B15, B20, B25 B50, B100 and conventional diesel are presented in Figure 4. From the figure, it can be observed that the NO_X emission increased with increase in the load and the emission increase was also proportional to biodiesel concentration. It was observed that NO_X emission increased from 10.6% to 37.7% for B5 to B100. The emission was maximum for Bl00 and minimum for B5. The large quantity of NO_X emitted was as a result of the high oxygen content in the biodiesel that reacted with the nitrogen component in the surrounding air (Jafarmadar and Pashae, 2013). The same trend was reported by Labeckas and Slavinskas (2006) who reported experimental work on a 7.31 Navistar engine running 13 mode US Heavy Duty test cycle using different soybean-oil biodiesel blends. They observed that an increase in NOx emission obtained was in proportion to the concentration in biodiesel and 8% increase was reached when 100% biodiesel was used. On the other hand, some researchers reported that the effect of biodiesel on NOx emissions depends on the types of engine and conditions of operation (Serdari et al., 1999; Hamasaki et al., 2001). Also, Serdari et al. (1999) measured on-road emissions from three different vehicles using high sulfur diesel fuel and 10% of sunflower biodiesel blends. They discovered both increase and decrease in NOx emissions and attributed such difference to the different engine maintenance culture and technology. Similarly, Hamasaki et al. (2001) tested a single-cylinder engine at 2000 rpm and varying loads with three waste-oil biodiesel fuels. They measured a slight reduction in NOx emission at low loads but increase at high loads. Tan et al. (2012) concluded from his findings that NOx emission with biodiesel fuels are usually higher when they are measured in an engine test bench than those from conventional diesel, but lower when they are measured from moving vehicles. The reason pointed out was that engine loads are usually lighter in moving vehicles than those imposed in experimental test beds. Furthermore, Durbin et al. (2000) tested pure biodiesel and a 20% biodiesel blend in four different engines. The engines were chosen to represent a wide variety of heavy-duty engines: turbocharged and naturally aspirated, direct and indirect injection. Little variations were found in NOx emissions and the researchers concluded that there are no significant differences between the two fuels. They attributed similarities in NOx emission to low unsaturation level of biodiesel (Nabi et al., 2006). Quite number of literatures also reported a decrease in NOx emissions when using biodiesel fuels. Peterson and Reece (1996) used several blends of fuels mixed with both ethyl and methyl esters from rapeseed oil in vehicles equipped with similar engines. They measured reductions in NOx emissions of around 10% both ester blends (as reported by Graboski and McCormick, 1998). Dorado et al. (2003) recorded reductions of above 20% from testing biodiesel from waste olive oil in an eight-mode cycle. Lastly, the formation of NO_X depends on cylinder temperature, ignition delay and oxygen content in the fuel, longer chain length and higher amounts of unsaturated fatty acids in methyl ester have been reported to correlate with an increase in NO_X emission (Kumar, 2014). In addition, most of the researches report that the increase in NO_X emission with biodiesel was as a result of the advanced combustion process as a consequence of the advanced injection derived from the physical properties of methyl ester (viscosity and density) (Cardone et al., 2002). Graboski and McCormick (1998) reported that characteristics of the injected fuel, such as droplet size distribution, droplet moment of inertia, air entrainment, penetration, fuel evaporation, and heat dissipation are all affected by the fuel properties: viscosity, surface tension, and boiling temperature. All these physical phenomena may have some influence on the delay time, diffusion combustion ratio and, in consequence, on the NO_X formation.

3.4 O_2 emission

Figure 5 shows that O_2 emission for the blends of biodiesel is higher than that of the diesel. The reason being that biodiesel is an oxygenated fuel and it contains oxygen of about 11% by volume, as a result of the higher density of biodiesel, hence, high oxygen content leading to complete combustion (Krishna et al., 2016). The presence of oxygen in methyl ester results in higher heat release during the premixed phase of combustion. Also, from the Figure 5, it can be observed that as the load increases the O_2 reduces and O_2 increased as biodiesel concentration increased. Lin and Li (2009) compared biodiesel from waste cooking oil and marine fish-oil in the engine and reported that the marine fish-oil biodiesel has a larger O_2 emission. The burning marine fish oil biodiesel formed slightly more O_2 than that of the commercial biodiesel from waste cooking oil, due to the slightly lower equivalence ratio of the former.

3.5 CO emission

Variations of CO emission at various biodiesel blends and loads are presented in Figure 6. Given all fuel compositions, CO emission reduced as loads and biodiesel concentration increased. As the quantities of raw biodiesel increased in blends; CO emissions of blends reduced because of increase in oxygen content which is as a result of the low calorific value of biodiesel fuel. With reference to most of the literature reviewed, decrease in CO emissions when substituting biodiesel for conventional diesel fuel can be considered as the general trend (Hansen and Jensen, 1997; Pinto et al., 2005; Shi et al., 2005). The result of this research work was also confirmed by the work of Aydin and Bayindir (2010) who reported that the effect of B5, B20, B50, B75, B100 and diesel fuel on the engine and found that minimum CO emission values were observed for B50, B75 and B100 due to the higher oxygen content compared to diesel fuels. A similar trend was reported from reviewed work carried out by Krahl et al. (2003) and found 15% reduction when using biodiesel as an alternative for diesel fuel. Load conditions were proved to have a remarkable effect on CO emissions (Lapuerta et al., 2008). Ramadhas et al. (2005) found that the engine releases more CO using petroleum diesel as compared to that of biodiesel blends under all loading conditions when rubber seed oil methyl was used to power a four stroke, direct injection, naturally aspirated single cylinder engine. In addition, Choi et al. (1997) fuelled single-cylinder research engine with biodiesel from soybean oil. They reported that there was no major difference in CO emissions at low loads, but the decrease was recorded at high loads. Several reasons were found to explain the general CO emission reduction when substituting biodiesel for conventional diesel. The additional oxygen content in the biodiesel fuel enhances a complete combustion of the fuel, thus reducing CO emissions (Pinto et al., 2005; Ullman et al., 1994). The advanced injection and combustion when using biodiesel may also justify the CO emission reduction when compared to conventional diesel fuel (Storey et al., 2005).

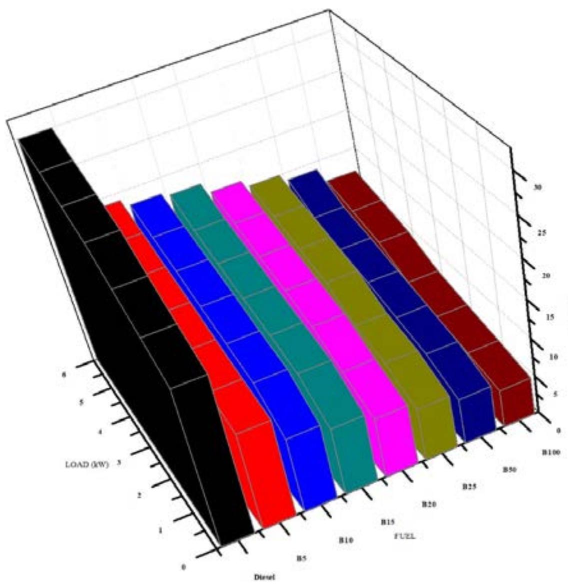

Figure 2 HC vs load for various blends

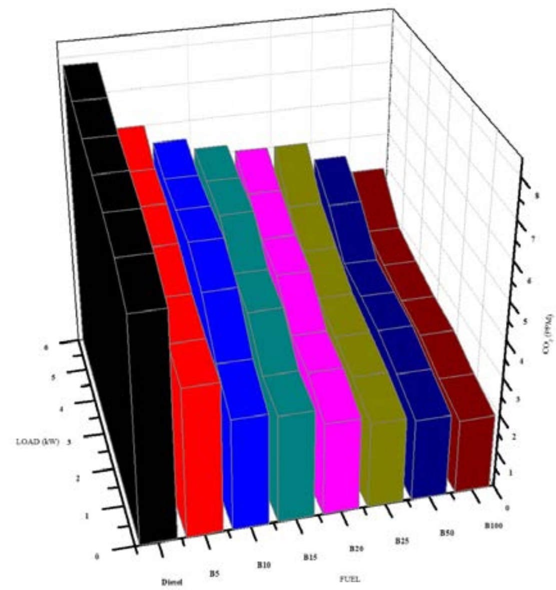

Figure 3 CO_2 vs load for various blends

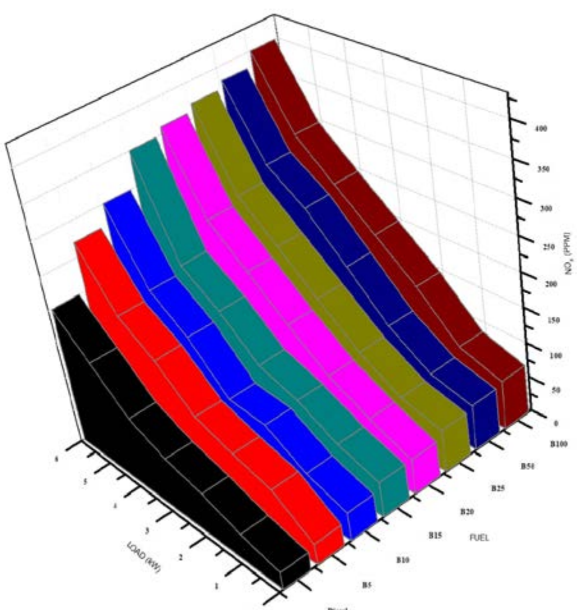

Figure 4 NO_X vs load for various blends

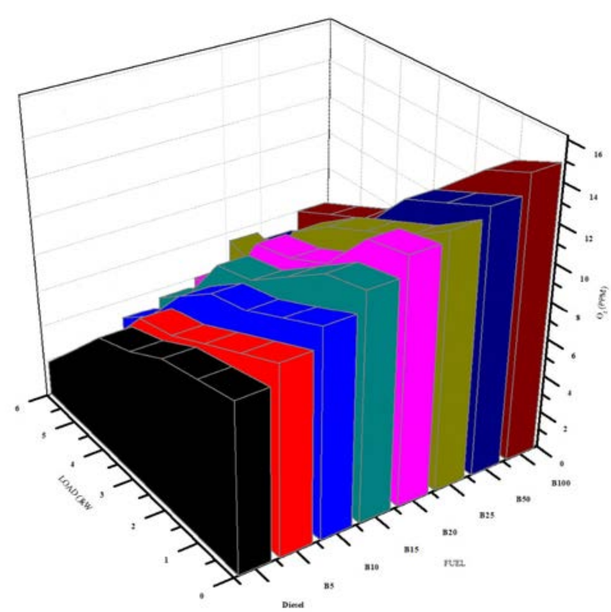

Figure 5 O_2 vs load for various blends

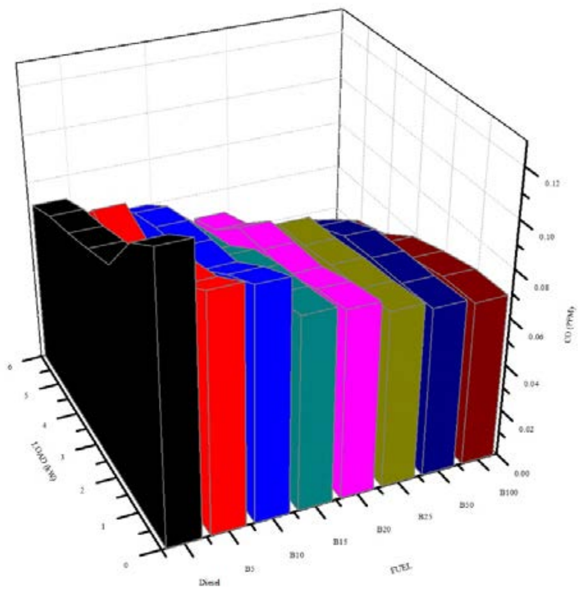

Figure 6 CO vs load for various blends

4 Conclusion

The physico-chemical properties of castor biodiesel and its blends with diesel were found to be similar to that of convectional diesel, and largely within limits specified by the ASTM D-6751, EN-14214, and IS-15607 standards except for B50 and B100. Performance and emissions of a diesel engine fuelled with 5%, 10%, 15%, 20%, 25%, 50% and 100% (by volume) of castor biodiesel and conventional diesel were experimentally investigated at different loading conditions. The results indicate compression ignition engine running with biodiesel highlights a significant reduction in CO_2, CO and HC emission under different loading conditions. It is also found that when the biodiesel concentration increases a further reduction in emissions was observed. This emission reduction is as a result of the oxygen content in biodiesel and the low carbon-hydrogen ratio. Also, for all biodiesel contents the NO_X and O_2 emission increases for all loading conditions of the engine. This increase may be explained by the higher oxygen content present in biodiesel and the advanced injection characteristics. Castor biodiesel offer petroleum like engine performance while still maintaining reductions in major emission gases. It is therefore recommended to farmers to use on farm fuel that is environmentally friendly and readily available.

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