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Emission Performance of a Diesel Engine Running on Biodiesel Fuel at Different Compression Ratios

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In the present study emission performance of a diesel engine (Lister Petter) was evaluated at different compression ratios and engine loads with soybean methyl ester and its 25%, 50%, 75% blends with diesel fuel at constant speed 1500 rpm. Exhaust emissions included CO, CO_2, HC and NO_x. The compression ratio and engine load varied from 14 to 20 with an interval 1 and 25 to 100% with an interval 25%, respectively. The experimental results indicated that for all combination of compression ratios and engine loads, it could be concluded that B75 and B100 could be safely blended without significantly affecting the emissions (CO, CO_2, HC and NO_x). Concerning the costs, B75 is more economical than B100. Thus B75 could be a cleaner, more appropriate alternative fuel than pure diesel.

Keywords: Compression ratio, Engine load, Exhaust emissions, Soybean methyl ester

1 Introduction

Biodiesel is the mono-alkyl esters of long chain fatty acids derived from a renewable lipid feedstock, such as vegetable oils or animal fats [1]. It can be classified as a combustible rather viscous liquid consisting of alkyl esters of fatty acids derived from vegetable oil or cooking grease. It is also described as fatty acid methyl esters prepared from any kind of biological feedstock including vegetable oil, animal fat, single cells oil and waste material [1, 2]. Biodiesel has various advantages; for instance, it can be used as complement or substitute to petroleum based fuel. Moreover, it is a renewable fuel, it has a favorable energy balance, it presents less harmful emissions and it is a non-toxic fuel, which makes it very attractive [2, 3, 4]. The growing concern due to environmental pollution caused by the conventional fossil fuels and the realization that they are non-renewable have led to a search for more environmentally-friendly and renewable fuel [5].

A number of studies have found that biodiesel compared to pure diesel could successfully reduce CO, CO_2, HC emission and increases NO_x emission .Krahl *et al.* [6] observed about 50% reduction in CO emission for biodiesel from rapeseed oil compare to low and ultra-low sulphur diesel. Raheman and Phadatare [7] have found that the reduction range of CO emission was 73-94% for the karanja methyl ester (B100) and its blends (B20, B40, B60, B80) compared to pure diesel. Murillo et al. [8] obtained that at full load, the CO emissions of diesel were the highest compared to biodiesel. Song and Zhang [9] reported that with an

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increase in biodiesel percentage in the blends, there was no obvious difference in the CO emission at partial loads, but it fluctuated at full load. Many researchers reported that biodiesel result in fewer CO_2 emissions than diesel during complete combustion [10-15]. However, some literature [16-21] reports that CO_2 emissions rise for biodiesel compared to diesel. Biodiesel will cause 50-80% reduction in CO_2 emissions compare to petroleum diesel [22, 23]. HC emissions reduce when pure biodiesel is fluted instead of diesel [10, 24-27]. Wu et al. [28] reported that the 5 different biodiesels reduced HC emissions by 45-67% on average compared with diesel fuel. Puhan et al. [29] found that the HC emissions reduced approximately around 63% for biodiesel compared to diesel. There are different conclusions about the effect of engine load on HC emissions for biodiesel. Lertsathapornsuka *et al*. [30] showed experimentally the increase in HC emission with load increase. While Tat *et al*. [31] found that HC emissions for biodiesel reduce as load increases. Much literature shows that NO_X emission rise with an increase in the content of biodiesel [7, 8, 32-34]. Luján *et al*. [35] observed that NO_x emissions increase to amount 20.6%, 25.9% and 44.8% for B30, B50 and B100, respectively. Of course, some researchers have found that the increase in the content of pure biodiesel follows no certain rules. Labeckas and Slavinskas [20] found that the B35 blend produced the maximum NO_x values compared to the other blends, including the pure biodiesel rapeseed methyl ester. Sahoo *et al*. [15] observed that the NO_x emissions for B20 increased to be 2% higher but B100 biodiesel blend produced 4% lower NO_x emissions. Some researchers studied the effect of Biodiesel content in diesel fuel on Specific Fuel Consumption (SFC). They reported that a minor increase in SFC was observed with biodiesel and its blends when compared with diesel fuel [40, 41].

In this study, effects of comparison ratio and engine load on exhaust emissions were investigated with various soybean methyl ester-diesel fuel blends. Also the effects of fuel blends (B0, B25, B50, B75 and B100) were studied on SFC at maximum engine speed (1800 rpm). Experiments were taken at four different engine loads.

2 Experiments

A single-cylinder Lister Petter engine was applied in this research. The engine was run using biodiesel obtained from soybean oil (B100), its blends with diesel fuel (B25, B50, B75) and diesel fuel. The tests were performed at constant speed 1500 rpm, at varying compression ratios (from 14 to 20 with an interval 1) and varying loads (from 25 to 100% with an interval 25%) to evaluate exhaust emissions including CO, CO_2, HC and NO_x. The experimental setup is shown schematically in Figure (1).

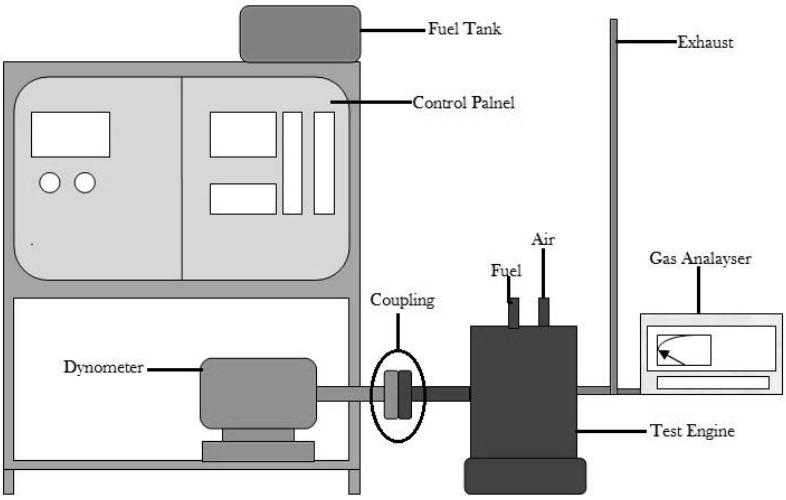


Figure 1 Engine test setup

Table 1 Specification of the Lister Petter engine

Particulars	Details
Type	Direct injection
Number of cylinders	1
Cooling	Water
Valve arrangement	Overhead camshaft, two vertical valves
Cylinder bore × stroke (mm)	90 × 120
Cycle	4-Stroke
Maximum Speed (rpm)	1800
Maximum Power (kW)	12
Maximum Torque (Nm)	24
Fuel Consumption	1.2 l/h (at full load)
Compression Ratio	Varied from approximately 23:1 down to 13:1

2.1 *Experimental Setup*

The compression ratio of the engine was varied from 14 to 20 with an interval 1 by lowering and raising a piston in another cylinder at the top of combustion chamber, using a piston hand linked to the piston. Compression ratio was varied by turning the piston hand. The movement of the piston was measured by means of a micrometer fitted on the cylinder.

The engine was coupled to an eddy current electrical dynamometer and loaded by electrical resistance. For applying load on the engine, the load switches were turned on and as a result, there was an increase in electrical resistance. By turning on each of the load switch 2.4 Nm was loaded on the engine. There were 20 load switches. Therefore, the maximum load, which the engine could take, was 48 Nm. This was taken as 100% load. The engine load was varied from 25, 50, 75 and 100% which are equal to 12, 24, 36 and 48 Nm load, respectively.

The motor speed was measured by a digital tachometer and it was fixed at 1500 rpm.

2.2 *Biodiesel*

The soybean oil was initially placed in a reactor. A mixture of methanol (6:1 methanol to oil molar ratio) and sodium hydroxide (1.0% based on weight oil) was then added to the reactor. The temperature and string speed of the reaction mixture were maintained constant for 1 h at 50°C and 600 rpm, respectively. After the reaction, biodiesel was separated from glycerin by centrifugation. Finally the biodiesel was blended with diesel fuel. The fuels properties were determined using the ASTM D6751 standards. The properties of the fuels are shown in Table (2).

Table 2 Measurement range and accuracy of MODAL 2010-AO gas analyzer

Measured gas	Measuring range	Accuracy
CO	0-15%	±0.5%
CO2	0-20%	±0.06%
HC	0-2000 ppm	±12 ppm
NOx	0-5000 ppm	±32ppm in range 0-1000ppm ±60ppm in range 1001-2000ppm ±120ppm in range 2001-5000ppm

Table 3 Fuel properties of soybean methyl ester and blends with diesel

Fuel Properties	Diesel	B25	B50	B75	B100	ASTM Method
Density (kg/m^3)	823	835	840	857	865	D4052
Viscosity (mm^2/s)	3.162	3.314	3.609	4.175	4.360	D445
Flash Point (°C)	45	57	65	73	106	D93
Pour Point (°C)	-12	-6	-3	1	3	D97
Cloudy Point (°C)	-2.2	-3.1	-4	-4.8	-5.9	D2500
Calorific Value (Mj/kg)	44.869	43.653	43.119	41.203	39.969	D240
Cetane Number	63	69	75.56	79.20	81.60	D976
Acid Value (mg KOH/g)	0.21	0.27	0.32	0.39	0.46	D664
Water Content (%)	0.01	0.01	0.02	0.03	0.02	D1533
Ash Content (%)	0.13	0.11	0.10	0.09	0.07	D482

2.3 Emission measurement

The exhaust gases were sampled from exhaust line by a specially designed arrangement for diverting the exhaust to the sampling line with no effect on the back pressure. The samples were analyzed using a multi-gas analyzer (MODAL 2010-AO, NAPRO Inc.).

The measurement range and the accuracy of the instrument used are given in Table (3).

2.4 Experimental procedure

At first, the engine was set at a compression ratio of 20 and not applying any load on the engine. After the calibration of the measurement devices and before each test, the engine was warmed up for about 10 minutes until the engine reached stable working condition. Then, the motor speed was stabilized on 1500 rpm and for various fuels; the engine was investigated at 25, 50, 75 and 100% loads. Being run for at least 5 minutes at each load condition in order to measure the exhaust emissions and then the data was collected. The same steps were taken for the other compression ratios. The experiments were replicated three times.

2.5 Experimental design and statistical analysis

A randomized complete design was conducted with three replications. The fuel treatment was in five levels; diesel fuel, B25, B50, B75 and B100. The comparison ratio treatments was in seven levels; 14, 15, 16, 17, 18, 19 and 20. The engine load treatment was in four levels 25%, 50%, 75% and 100%. To detect significant difference, analysis of variance was adopted using SAS package.

3 Results and Discussion

Comparison of means of data on Specific Fuel Consumption (SFC) indicated that there was not any significant difference on this index for all types of fuel. According to Figure 2 it is seen that the SFC increases as the biodiesel content in blend increases. Owing to the fact that the heating value of biodiesel is lower than of diesel fuel, the SFC increases. The values of SFC were about 100 g/Kwh, 109.2 g/Kwh, 111.7 g/Kwh, 114.1 g/Kwh and 119.6 g/Kwh for B0, B25, B50, B75 and B100 fuels, respectively. SFC values obtained from B25 and B100 were about 9% and 32% higher than those with B0, respectively. Similar trend related to SFC were reported in Refs [40, 41].

In the following Figure (2), the effects of the type of the fuel, the compression ratio and the engine loading on exhaust emissions are shown. The results are discussed in the following sections.

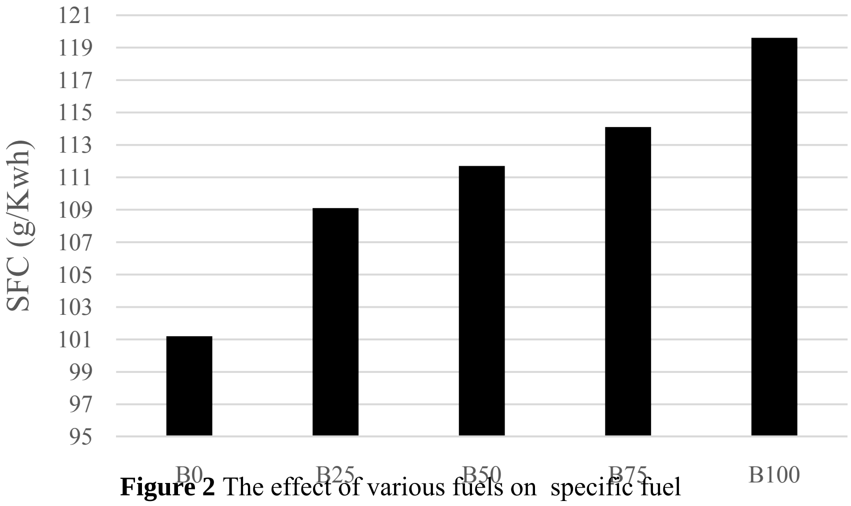


Figure 2 The effect of various fuels on specific fuel consumption.

3.1 CO emission

Comparison of the means of data on CO emission indicated that there wasn't any significant difference between B25 & B50 and B75 & B100, respectively (Figure 3). It was shown that CO emission decreased with an increase in pure biodiesel. All four aforementioned biodiesels resulted in lower CO emissions as compared to diesel fuel. The B100 resulted in the lowest amount of CO emission (Figure. 3). The reduction in CO emission is mainly due to higher oxygen content and lower carbon to hydrogen ratio in biodiesel compared to diesel according to Murillo et al.(2007) and Aydin and Bayindir (2010) [8, 36].

Table 4 Summary of analyses of variance

Source of variation	Fuel consumption	CO	CO_2	HC	NO_x
a[1]	ns[4]	*[5]	*	*	*
b[2]	ns	*	*	*	*
a×b	ns	*	*	*	*
c[3]	ns	*	*	*	*
a×c	ns	*	*	*	*
b×c	ns	*	ns	*	*
a×b×c	ns	*	*	*	*

1. Fuel types, 2. Compression ratio, 3. Engine load, 4. Non-significant, 5. Significant at 0.01 level

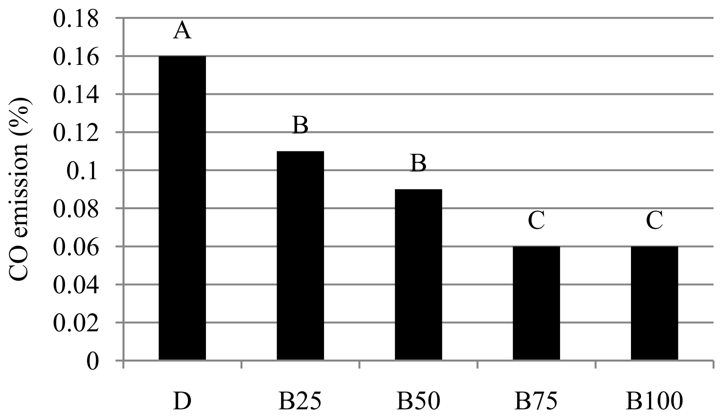
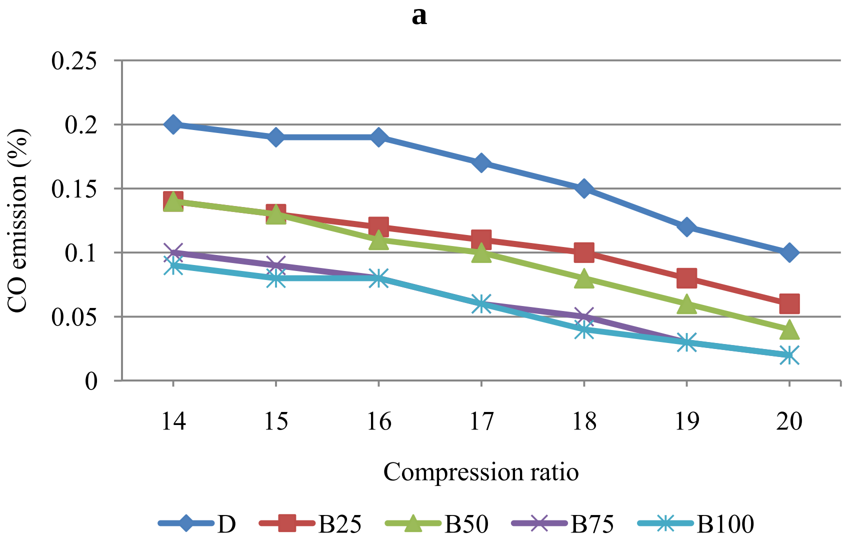


Figure 3 Overall percent CO emission for various fuels experienced at constant speed 1500 rpm.

Figure (4) shows CO emissions of different biodiesels at varying compression ratios and varying engine loads. The figure shows the CO emission variation of the engine for all the fuels in varying compression ratio. As shown in Figure (4a), CO emission decreased with an increase in compression ratio. At lower compression ratio, the temperature decreased and thus more CO is exhausted from the engine [37].

The variations which occurred in CO emission resulted from engine loading for different fuels are shown in Figure 4b. CO emission increased as a result of an increase in engine load. The main reason can be attributed to a decrease in the air-fuel ratio as a result of an increase in load [10]. Lower CO emission of biodiesel blends as compared to diesel fuel is due to their more complex oxidation [32]. For all the fuels investigated, it can be seen from Figure 4b that the variations in CO emission at upper load is more than lower load. The main reason for this trend is when no load is applied on the engine, the cylinder temperature tend to be too low and it can be increased by loading the engine resulted in more fuel injection inside the cylinder in upper loads [32].



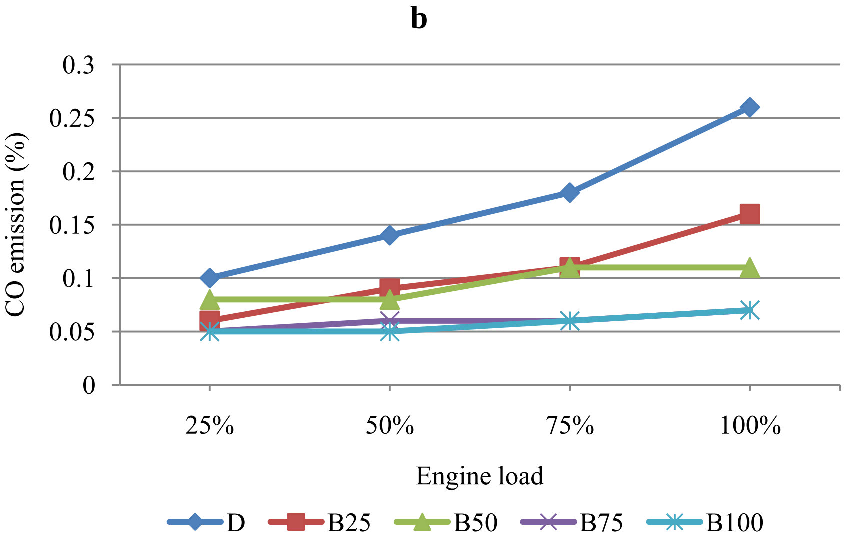


Figure 4 Variation of CO emission with compression ratio (a), and engine load (b) for biodiesels and its blends with diesel fuel at constant speed 1500 rpm.

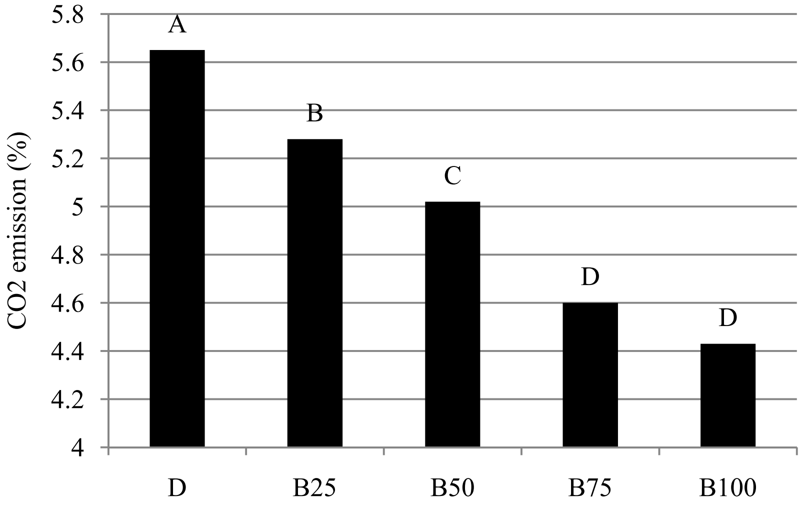


Figure 5 Overall per cent CO_2 emission for various fuels experienced at constant speed 1500 rpm.

3.2 CO_2 emission

Comparison of the means of the data on CO_2 emission revealed that there was no significant difference between B75 and B100 Figure (5). It is clear from the figure that when biodiesel was replaced by diesel fuel, CO_2 emission decreased. By increasing the replaced pure biodiesel into diesel fuel from 25 to 100%, the CO_2 which was produced decreased from 5.65 to 4.43%. Due to lower carbon to hydrocarbon ratio, biodiesel resulted in fewer CO_2 emissions as compared to diesel fuel [11, 12, 15].

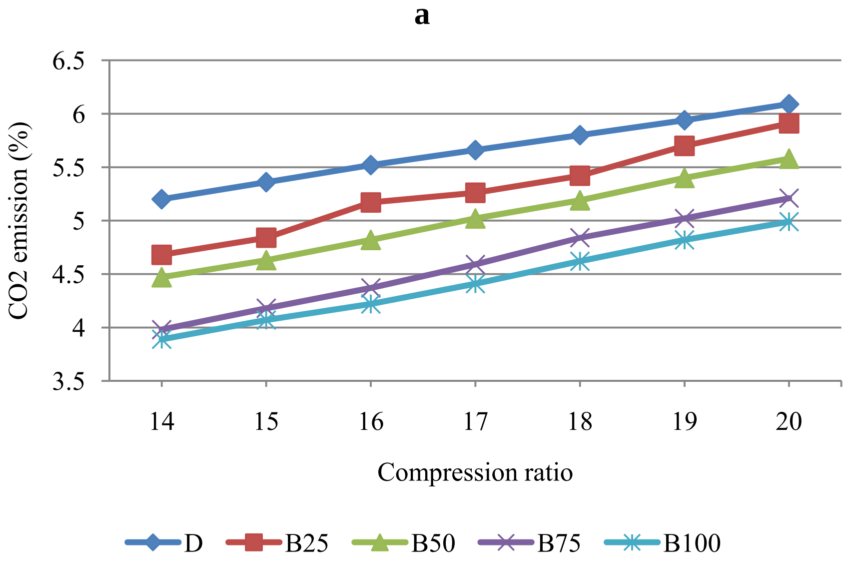
Figure (6) shows the variation in CO_2 emissions of the engine using different biodiesels at varying compression ratios and engine loading.

Figure (6a) shows the CO_2 emission for different fuel by increasing compression ratio. It can be seen from the Figure that by increasing compression ratio CO_2 emission increased for different fuels. This increase can be caused a better combustion at higher compression ratio

[37]. The biodiesel fuel and its blends produce lower CO_2 emissions as compared to pure diesel for all of the compression ratios. Lower carbon to hydrocarbon ratio can be the possible cause of this decrease [11, 12, 15]. CO_2 emissions for all of the fuels experimented at varying engine loading are shown in Figure (6b). For different fuels, CO_2 emissions tend to increase with an increase in engine loading. Figure (4b) shows a considerable increase in CO_2 emission, when the engine loading increased from 75 to 100%. The reason for the increase in CO_2 emission at high load is a decrease in the air-fuel ratio [10].

3.3 HC emission

Figure (7) shows the HC emission produced by different fuels. No significant differences were found between diesel fuel & B25 and B75 and B100, respectively. From the figure, it can be seen that HC emission reduced when pure biodiesel is applied instead of diesel. HC emissions approximately reduced to 26% for B100 as compared to pure diesel. Theoretically, HC emission is mainly caused by misfire in a locally reach or lean region. The difference in HC emission using difference fuels may be the result of the effects of oxygen content and Cetane number [28]. As can be seen in Table (2), when the amount of biodiesel in the blends increases, there is an increase in Cetane number as well. An increase in Cetane number results in a decrease in HC emission for biodiesels, but due to existence of oxygen in biodiesel molecules, the HC emission for biodiesels is lower than that of pure diesel [28].



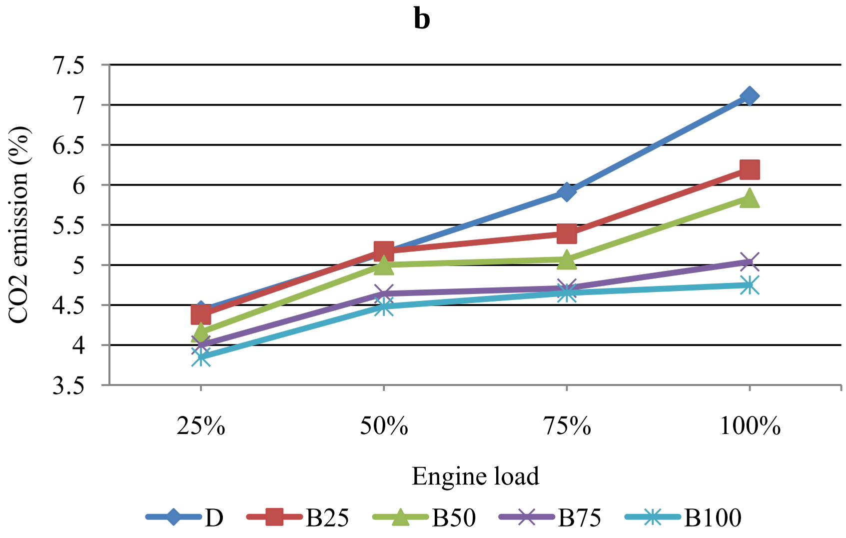


Figure 6 Variation of CO_2 emission with compression ratio (a), and engine load (b) for biodiesels and its blends with diesel fuel at constant speed 1500 rpm.

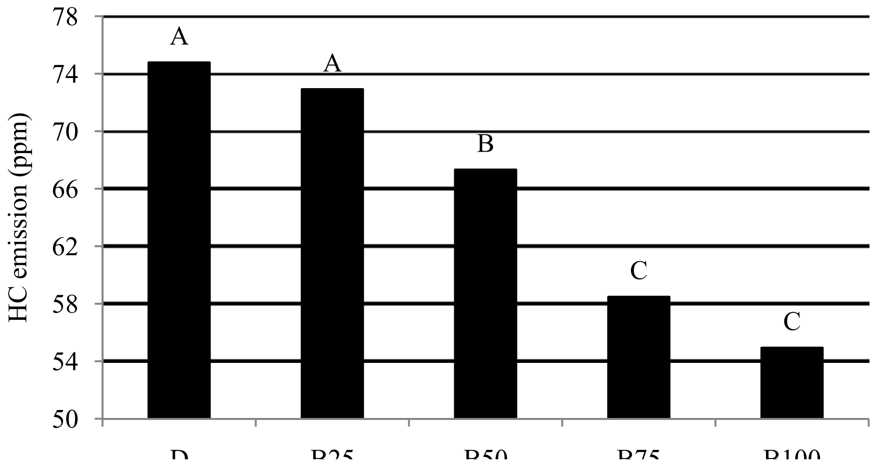
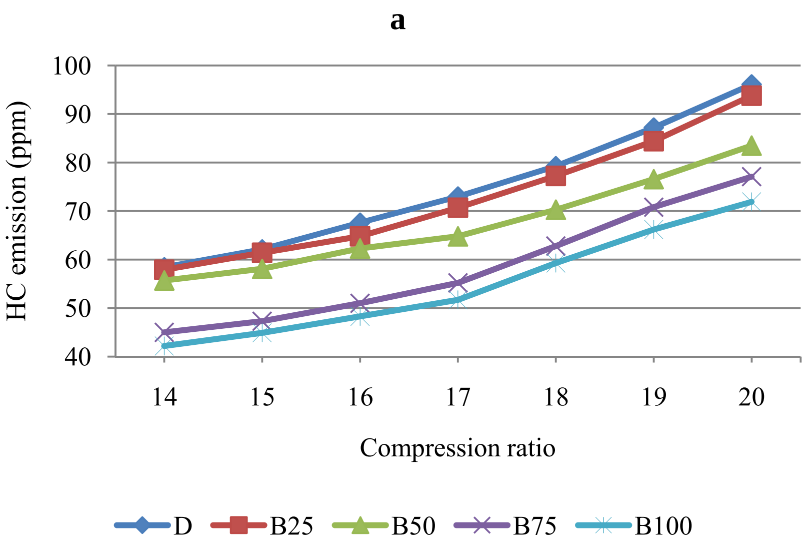


Figure 7 Overall HC emission for various fuels experienced at constant speed 1500 rpm.



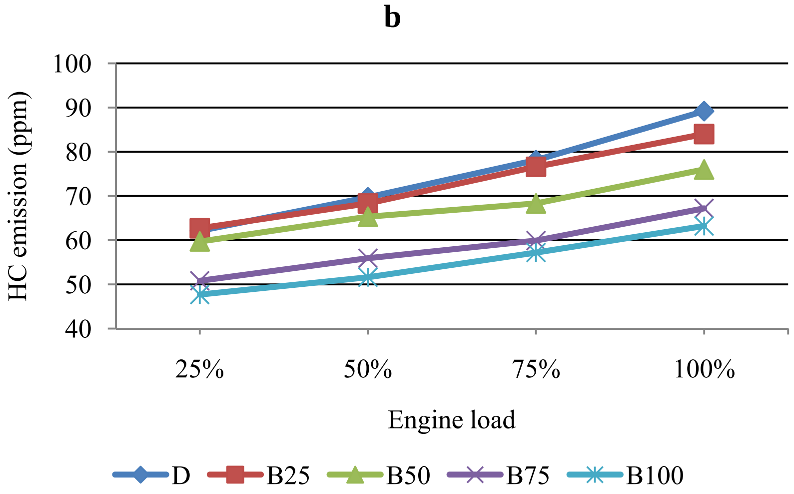


Figure 8 Variation of HC emission with compression ratio (a), and engine load (b) for biodiesels and its blends with diesel fuel at constant speed 1500 rpm.

The variations in HC emission resulting from varying engine load for different fuels are shown in Figure (8a). As shown in the Figure, HC emissions increased with an increase in compression ratio. The minimum HC emissions were found in compaction ratio 14 for B100. At lower compression ratios, inadequate heat of compression delays ignition whereas at high compression ratio, dilution by residual gases hampers the combustion [37]. It is seen in Figure (6a) that for all of the compression ratios, HC emissions for biodiesel fuel and its blends are lower as compared to pure diesel. The reduction in HC emissions is principally due to the fact that biodiesel has about 10-11% oxygen contents which help in better combustion of the fuel inside the cylinder [37].

Figure (8b) shows the plots of HC emission for different fuels. It was observed that the HC emission increases with an increase in engine loading. One of the most important parameters causing this increase is high fuel consumption in high load [30].

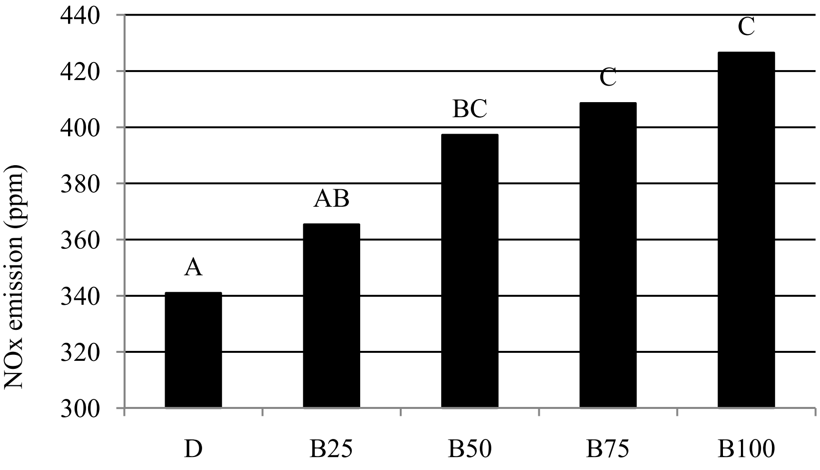


Figure 9 Overall NO_x emission for various fuels experienced at constant speed 1500 rpm.

3.4 NO$_x$ emission

No significant difference was noticed on NO$_x$ emission between diesel fuel & B20, B25 & B50 and B50, B75 & B100 (Figure 9).

The variations of NO$_x$ values as parts per million (ppm) for various fuels are shown in Figure (8). It can be seen that as biodiesel content increased in pure diesel, NO$_x$ emission also increased. The B100 produced the maximum NO$_x$ values than the other fuels. High exhaust gas temperature in biodiesels as compared to pure diesel and the oxygen content in biodiesel helped NO$_x$ formation [15, 38].

The variations in NO$_x$ emission resulting from variations in compression ratio for different fuels are shown in Figure (10a). The highest emissions were seen in high compression ratio. The emission of NO$_x$ for B100 is more sensitive to compression ratio when it increases from 18 to 20. As compression ratio increased, there was an increase in exhaust gas temperature and hence resulting in NO$_x$ formation.

Figure (10b) shows the NO$_x$ emission variation for all the fuels, as the load increases. NO$_x$ emission increased when the load was increased. As the load was increased, the overall fuel-air ratio increased which resulted in an increase in the average gas temperature in the combustion chamber and hence NO$_x$ formation [5, 25, 39].

4 Conclusions

The experimental results indicated that for all combination of compression ratios and engine loads, it could be concluded that B75 and B100 could be safely blended without significantly affecting the emissions (CO, CO$_2$, HC and NO$_x$). Concerning the costs, B75 is more economical than B100. Thus B75 could be a cleaner, more appropriate alternative fuel than pure diesel.

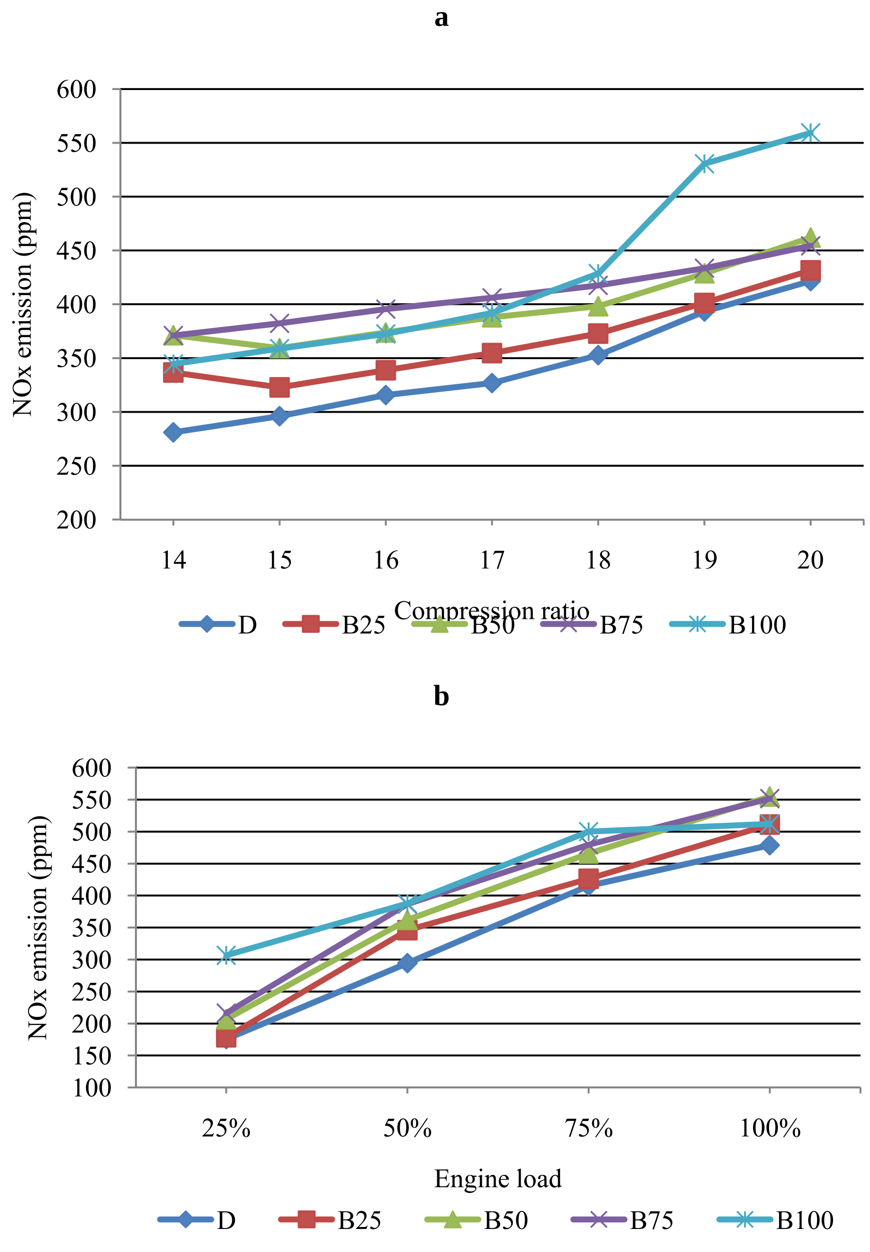


Figure 10 Variation of NO_x emission with compression ratio (a), and engine load (b) for biodiesels and its blends with diesel fuel at constant speed 1500 rpm.

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Nomenclature

CO: carbon monoxide
CO_2: carbon dioxide
HC: hydrocarbons
NO_x: nitrogen oxides
B25: 25% soybean methyl ester and 75% diesel
B50: 50% soybean methyl ester and 50% diesel
B75: 75% soybean methyl ester and 25% diesel
B100: 100% soybean methyl ester

چکیده

در تحقیق حاضر عملکرد یک موتور دیزل (Lister Petter) در نسبت تراکم های مختلف (۱۴:۱ تا ۲۰:۱ با فاصله ثابت ۱) و بارهای مختلف (۲۵٪، ۵۰٪، ۷۵٪ و ۱۰۰٪) هنگام مصرف سوخت بیودیزل تهیه شده از متیل استر سویا و ترکیبات آن با سوخت دیزل (B25، B50، B75، B100) در سرعت ثابت ۱۵۰۰ دور بر دقیقه بر روی آلایندهای مختلف (CO، CO2، HC و NOx) ارزیابی گردید.

نتایج آزمایش‌ها نشان داد که برای همه ترکیبات نسبت تراکم و بار موتور سوخت های B75 و B100 را می‌توان به عنوان ایمنی ترین ترکیب بدون تاثیر معنی دار روی پارامترهای آلودگی در نظر گرفت. با توجه به بالا بودن هزینه های تولید سوخت بیودیزل خالص، سوخت B75 را می توان به عنوان جایگزین مناسب تری نسبت به سوخت دیزل معرفی کرد.