# Performance and Emission Characteristics of a Diesel Engine Fueled by Biodiesel-Ethanol-Diesel Fuel Blends

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**Abstract:** There is growing interest to study the effect of blending various oxygenated additives with diesel or biodiesel fuel on engine performance and emission characteristics. This study aims to analyze the performance and exhaust emission of a four-stroke, four-cylinder diesel engine fueled with biodiesel-ethanol-diesel. Biodiesel was first produced from crude Jatropha oil, and then it was blended with ethanol and fossil diesel in different blend ratios (B10E10D80, B12.5E12.5D75, B15E15D70, B20E20D60 and B25E25D50). The engine performance and emission characteristics were studied at engine speeds ranging from 1200 to 2000 rpm. The results show that the brake specific fuel consumption increases while the brake power decreases as the percentage of biodiesel and ethanol increases in the blend. The exhaust emission analysis shows a reduction in $CO_2$ emission and increase in NOx emission when the biodiesel -to- ethanol ratio increases in the blends, when compared with diesel as a reference fuel.

**Keywords**: Biodiesel; Ethanol; Diesel Engine Performance; Exhaust Emissions.

## 1. Introduction

Many researchers have studied the impact of blending various oxygenated additives with diesel or biodiesel fuel on engine performance and emission characteristics of diesel engines (Alptekin 2017; Khalife et al. 2017). The most investigated (in recent years) oxygenates are alcohols such as ethanol, methanol, propanol and butanol (Qi et al. 2010; Dharmaraj and Karuppannan 2014; Li et al. 2015; Yasin et al. 2015; Al-Samaraae et al. 2017; Jamrozik et al. 2017; Pinzi et al. 2017; Mahmudul et al. 2018). It is known that diesel fuel and alcohol have difficulties in mixing and exhibit a tendency of phase separation but biodiesel is known to be miscible with alcohols (Abu-Qudais et al. 2000; Jamrozik et al. 2017). Adding biodiesel as a solvent for ethanol in diesel fuel has been investigated by different researchers (Hulwan and Joshi 2011; Zhu et al. 2011; Jamrozik et al. 2017; Tutak et al. 2017).

Jamrozik et al. (2017) investigated the co-combustion of diesel-biodiesel-ethanol fuel blend in a direct injection diesel engine at constant rotational speed and different engine loads.

Their results revealed that with the increase of ethanol fuel concentration in the blend the ignition delay increased, but burning duration decreased. The fraction of ethanol fuel in the blend generally causes NOx emission to increase due to higher oxygen content and higher in-cylinder temperatures. Zhu et al. (2011) investigated the effect of co-combustion of diesel fuel, biodiesel and ethanol blends on the performance of a four-cylinder direct injection diesel engine. Blending 5% ethanol with biodiesel could improve the engine performance, in terms of brake thermal efficiency, and NOx, particulate, HC and CO emissions. Hulwan and Joshi (2011) investigated combustion using a high percentage of ethanol in diesel–ethanol blends, with biodiesel as a co-solvent. The blends tested were D70E20B10, D50E30B20, and D50E40B10. The results revealed that brake specific fuel consumption increased but the brake thermal efficiency was improved for high ethanol content blends. The NOx emission variation depended on operating conditions while CO emissions drastically increased at low loads.

Sudan has an increasing demand of fossil fuels for the requirements of transportation sector. There is a growing interest to produce biodiesel from Jatropha oil which could be blended with the available fossil diesel, despite the practical and economic issues of planting and harvesting of Jatropha at a commercial scale. On the other hand, Sudan has shown that biofuel production can be an economic proposition and is considered one of the largest producers of sugarcane and ethanol produced from sugarcane molasses in Africa (Ben-Iwo et al. 2016; Hess et al. 2016). In 2009 Kenana Sugar Company (KSC), the Sudan's largest sugar producer launched an ethanol production plant based on 1st generation technology (molasses fermentation) with the capacity to produce commercial high-grade ethanol with annual capacity of 65 million litres and with the aim to expand the production to 200 million litres per year by 2020. While 90% of this ethanol is presently exported to Europe, already some petrol stations in Sudan introduced E10 blend (Nile-Ultra) (Kumar and Priyanka 2016). Introducing ethanol in Jatropha biodiesel –diesel blend may decrease the Jatropha oil consumption and also enhance some important properties of the fuel blend such as density, viscosity and the presence of oxygen, which may enhance the combustion and spray characterization (Zaharin et al. 2017). This study aims to analyze the performance and exhaust emissions of a four cylinder, four stroke diesel engine fueled by biodiesel-ethanol-diesel fuel at an engine speed range between 1200 to 2000 rpm.

## 2. Materials and Methods

This section details the methodology adopted in this study. It includes the preparation of feedstock, production of biodiesel, preparation of the blends, and experiments using these blends in a four-stroke diesel engine. All equipment and instruments used during the study are also shown in this section. The methodology flow-chart is shown in Figure1.

### 2.1 Preparation of Feedstock

#### 2.1.1 Jatropha Oil

Jatropha curcas seeds were provided from South Kordofan State in the west of the Republic of Sudan. Firstly, the seeds were crushed and humidified before being put into a mechanical expeller to extract the oil. The sequence of these steps is shown in Figure 2. The main physical properties of Jatropha oil were determined as per standard methods and reported in Table 1.

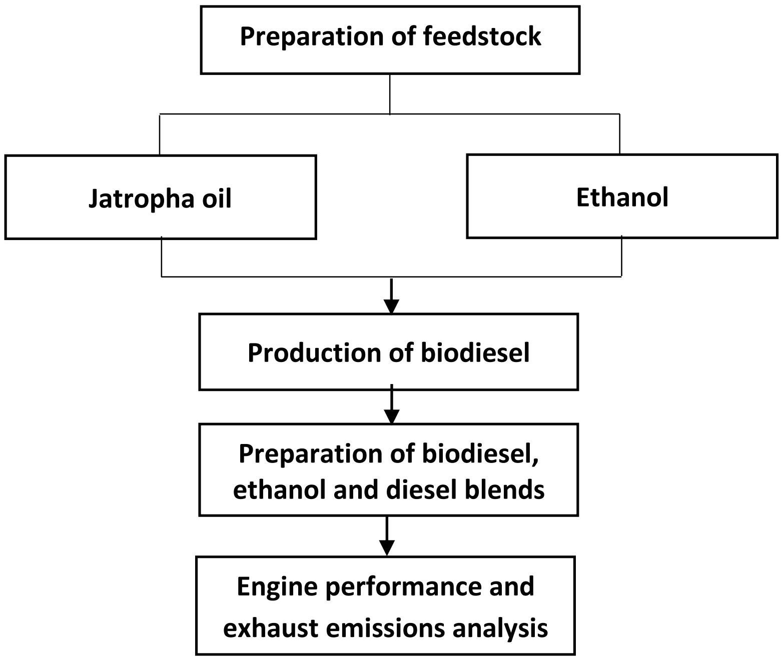


Figure 1: Methodology flow-chart.

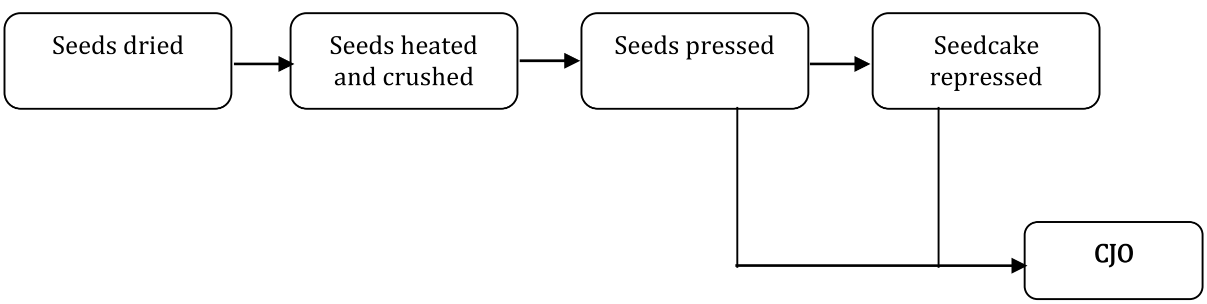


Figure 2: Crude Jatropha oil (CJO) extraction process.

### 2.1.2 Ethanol

The ethanol (ethyl alcohol, $C_2H6O6$) was obtained from Kenana Ethanol Alcohol Co. Ltd. It was produced from the sugar production by-product of molasses at an ethanol concentration of 99.7%. Table 2 list some of its properties.

Table 1: Physiochemical properties of Jatropha oil.

| Property | Value |
|---|---|
| Acid Value (mgKOH/g) | 2.3 |
| Density (g/cm$^3$) @15$^o$C | 0.933 |
| Kinematic viscosity (Cst) @40$^o$C | 50.73 |
| Flash point ($^o$C) | 205 |
| Calorific value (kJ/kg) | 39,649 |

Table 2: Properties of ethanol

| Property | Value |
|---|---|
| Density (g/cm$^3$) @ 20 $^o$C | 0.789 |
| Boiling point (˚C) | 78.5 |
| Heat of combustion (MJ/L) | 23.625 |
| Heat of vaporization (kJ/mole) | 33.74 |
| Octane rating | 106 - 108 |
| Stoichiometric air/fuel ratio | 9/1 |
| Water content | ≤ 0.3 |

### 2.1.3 Biodiesel Production

The transesterification process was adopted to produce biodiesel from crude Jatropha oil (Al-Samaraae et al. 2017). The crude Jatropha oil was firstly heated and filtered before entering the alkaline-catalyzed transesterification process. The oil was poured into a round-bottomed flask. The required amount of the catalyst sodium hydroxide (NaOH) was weighed and dissolved completely in methanol (MeOH) to form sodium methoxide (MeOH). Meanwhile, the oil was warmed, and the prepared methoxide was added to the oil at 60$^o$C. The reaction was conducted for two hours in a vigorous mixing mode. Then it was allowed to settle in a funnel for overnight to allow the removal of the glycerol layer which was formed in the bottom of the funnel. Following this, the produced methyl ester was washed three times with warm distilled water at 50°C till the pH of the washed water was less than 8. To remove the moisture, the final product was heated up to 100°C for 30 minutes. The sequences of the production steps and the setup used for biodiesel production are shown in Figure 3 and Figure 4 respectively.

### 2.1.4 Preparation of Biodiesel, Ethanol and Diesel Blends

The biodiesel produced was blended with the ethanol and the diesel fuel which were obtained from a local petroleum fuel station in Khartoum. The blends were made in the ratios of B10E10D80, B12.5E12.5D75, B15E15D70, B20E20D60, and B25E25D50 on a volumetric basis. For example, a B10E10D80 blend contains 10% of biodiesel, 10% ethanol and 80 % diesel fuel. The blends were performed simply by pouring the three fuels in a container at the correct ratios and mixing them until the blend is homogeneous.

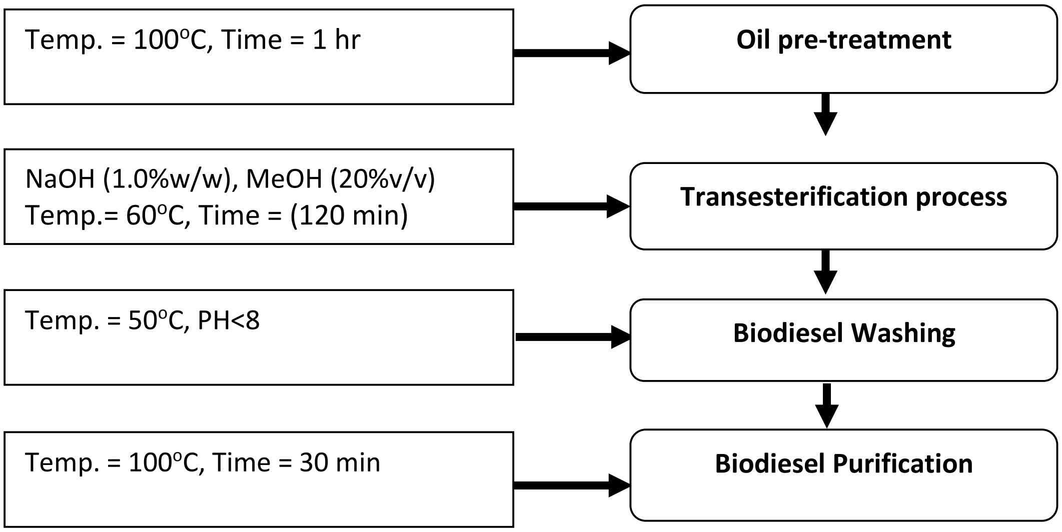


Figure 3: Biodiesel production process steps.

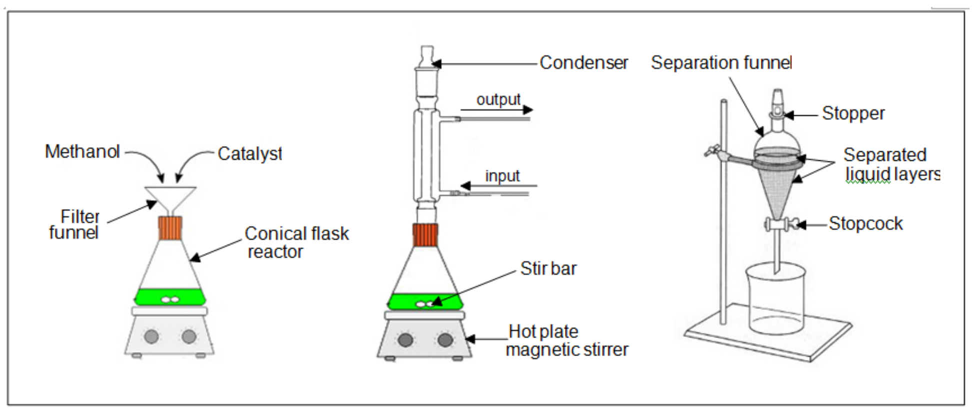


Figure 4: Biodiesel production setup.

Table 3: Specification of Toyota diesel engine

| Engine type | Toyota diesel engine |
|---|---|
| Cooling system | Liquid intercooler system |
| Cylinder arrangement | In – line |
| No of cylinder& valves | 4 cylinders 8 valves |
| Bore | 92 mm |
| Stroke | 92 mm |
| Compression ratio | 22.3 |
| Torque | 15.8–16.8 kgm |
| Fuel system | Direct injection |
| Displacement | 2.446cc |

## 2.2 Experimental Setup for Engine Test

The engine investigated in this study was a Toyota, four stroke, four-cylinder diesel engine. The engine specifications are shown in Table 3. The engine was coupled to a dynamometer to measure the output. To measure the exhaust emission gases of $CO_2$ and NOx, a multi-gas exhaust analyzer was used. To get the average values, all tests were repeated three times. The experimental investigation was carried out using the different fuel blends prepared, at engine speed ranged from 1200 rpm to 2000 rpm under constant engine load.

# 3 Results and Discussion

### *3.1 Properties of biodiesel, ethanol and diesel blends*

Some of the physical properties of the fuel blends were analyzed based on ASTM D6751 and recorded in Table 4. Increasing the ratio of biodiesel and ethanol in the blend was found to increase the density, the kinematic viscosity, and the flash point, and to decrease the calorific value (Table 4).

Table 4: Physical properties of biodiesel, ethanol and diesel blends

| No | Blend | Density @15 °C (g/cm³) | Kinematic viscosity (Cst) @40°C | Flash point (°C) | Calorific value (kJ/kg) |
|---|---|---|---|---|---|
| 1. | B10E10D80 | 0.868 | 5.2 | 65 | 43093 |
| 2. | B12.5E12.5D75 | 0.870 | 5.3 | 69 | 42106 |
| 3. | B15E15D70 | 0.872 | 5.4 | 78 | 42207 |
| 4. | B20E20D60 | 0.879 | 5.7 | 87 | 41106 |
| 5. | B25E25D50 | 0.882 | 5.9 | 94 | 40877 |
| 6. | B100 | 0.884 | 3.7 | 154 | - |
| ASTM D6751Limit | | 0.880 | 1.9-6.0 | 130 minimum | NA |
| Test Method | | D1298 | D445 | D93 | NA |
| *These tests performed at Central Petroleum Laboratories (CPL), Ministry of Gas and Oil* | | | | | |

### *3.2 Engine Performance*

The engine performance parameters investigated were, Brake Power (BP) and Brake Specific Fuel Consumption (BSFC). The engine exhaust gas constituents measured were Carbon Dioxide ($CO_2$), and Nitrogen Oxides (NOx). The equations used to calculate BP and BSFC were:

$$BP = \frac{(2\pi NT)}{60*1000}, \text{ where T is Torque (Nm) and N is speed (rpm)} \quad (1)$$

$$BSFC = TFC / BP, \text{ where } TFC \equiv \text{Total fuel consumption (kg/sec)} \quad (2)$$

### *3.2.1 Brake Power (BP)*

The variation of the engine brake power obtained for different fuel blends at various engine speeds is shown in Figure 5. It is obvious that the engine power increases with an increase in engine speed. Brake power output for all fuel blends is slightly lower than that for diesel fuel at range of speeds investigated. However, there is no significant difference in brake power between diesel fuel and biodiesel-ethanol-diesel blends except for B25E25D50 which gave the lowest brake power. Lower cetane number and lower calorific value of any fuel blend has a direct influence on the power output of the engine (Shahir et al. 2014; Aydogan 2015).

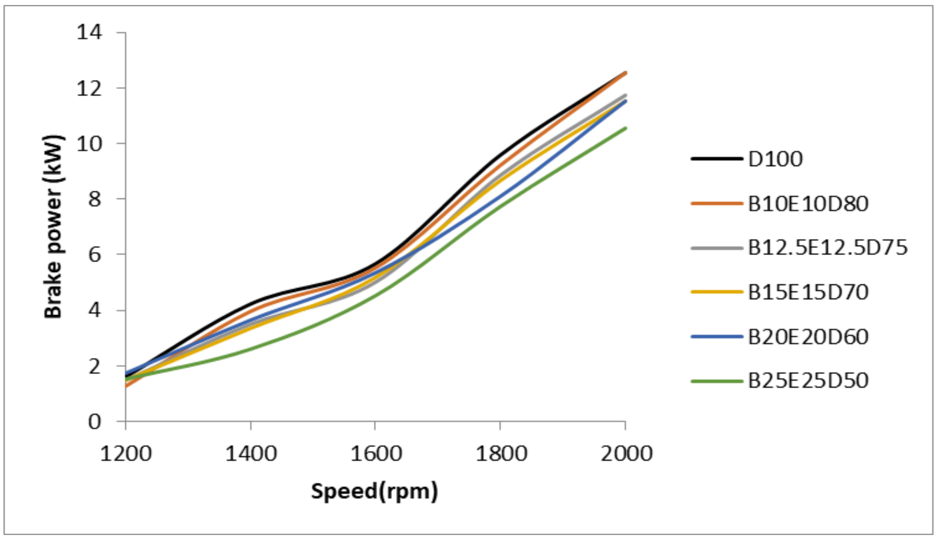

Figure 5: The variation of brake power with engine speed.

### 3.2.2 Brake Specific Fuel Consumption (BSFC)

The BSFC of biodiesel, ethanol and diesel fuel blends was investigated and compared with BSFC of diesel fuel at different engine speeds, as shown in Figure 6. Generally, BSFC decreases at low range of speed until a certain point, and then starts to increase. For all fuel blends BSFC started to increase after 1400 rpm compared to BSFC for diesel fuel which started to increase after 1600 rpm. The overall BFSC for the fuel blends is higher than that of diesel fuel in the entire range of engine speeds examined, except for B10E10D80 where the BSFC is lower than BSFC of diesel fuel for the speed range less than 1500 rpm. The calorific value of the fuel blends tends to decrease with the increase of the ratio of biodiesel and ethanol as a result of the lower calorific value of each of them, which increases the amount of fuel required for the combustion at any level of load (Hulwan and Joshi 2011; Shahir et al. 2014; Aydogan, 2015).

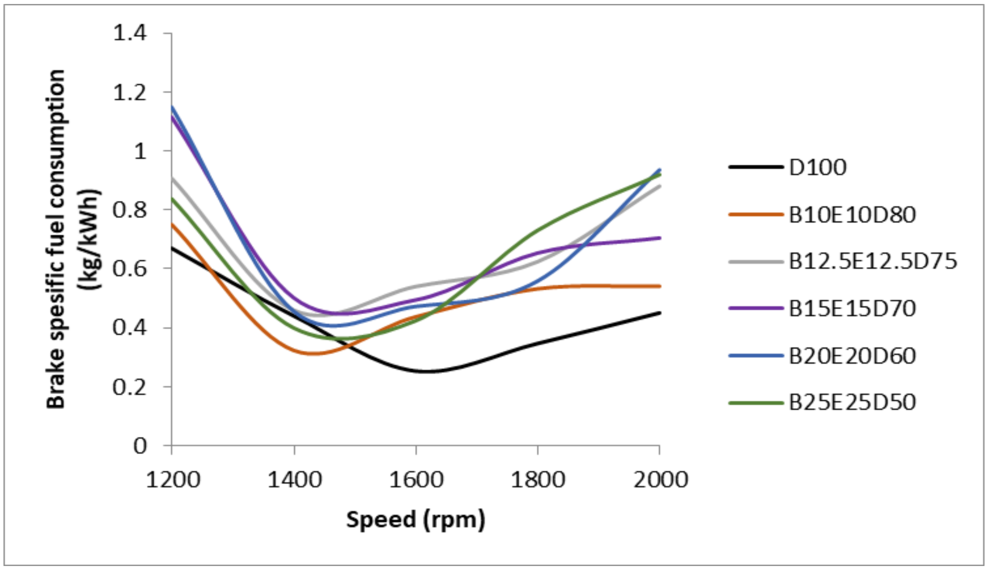


Figure 6: The variation of brake specific fuel consumption against engine speed.

## 3.3 Exhaust emissions

### 3.3.1 Carbon dioxide ($CO_2$) emission

The variation of $CO_2$ emission with engine speed for all fuel blends is presented in Figure 7. It is found that the $CO_2$ emission decreases with the increase of biodiesel-ethanol ratio in the fuel blend for the entire range of engine speed. However, the lowest $CO_2$ emission is reported when using B25E25D50. $CO_2$ emission indicates how efficiently the fuel burns inside the combustion chamber. This is assumed to be due to the lower carbon-to-hydrogen ratio in biodiesel and ethanol or presence of more oxygen in the fuel blends (Tutak et al. 2017).

### 3.3.2 Nitrogen Oxide (NOx) emission

NO is the dominate fraction of the oxides of nitrogen produced inside the engine cylinder. The oxidation of molecular nitrogen is the principle source of NO emissions. Figure 8 shows the variation of NOx emissions with engine speed, when utilizing biodiesel-ethanol-diesel blends when compared with diesel as a fuel. It is clear that the NOx emission profiles for diesel fuel and fuel blends tested increase with an increase in engine speed. Increasing the biodiesel and ethanol percentage in the blend produces higher NOx emissions compared to when running on diesel fuel. This is explained by the fact that higher oxygen percentage in biodiesel and ethanol leads to a richer mixture being combusted in the cylinder when compared to diesel fuel (Dharmaraj and Karuppannan 2014). Cetane number, unsaturated compounds and different injection characteristics can also have an impact on increasing NOx emissions for an increasing ratio of biodiesel and ethanol in the blend. The presence of ethanol and biodiesel in the blend decreases cetane number significantly and causes increase in ignition delay period, which results in a richer fuel/air mixture entering the combustion chamber, causes a rapid heat release at the beginning of the combustion, and results in higher temperature and higher NO*x* formation (Kwanchareon et al. 2007; Takeda et al. 2014; Jamrozik et al. 2017).

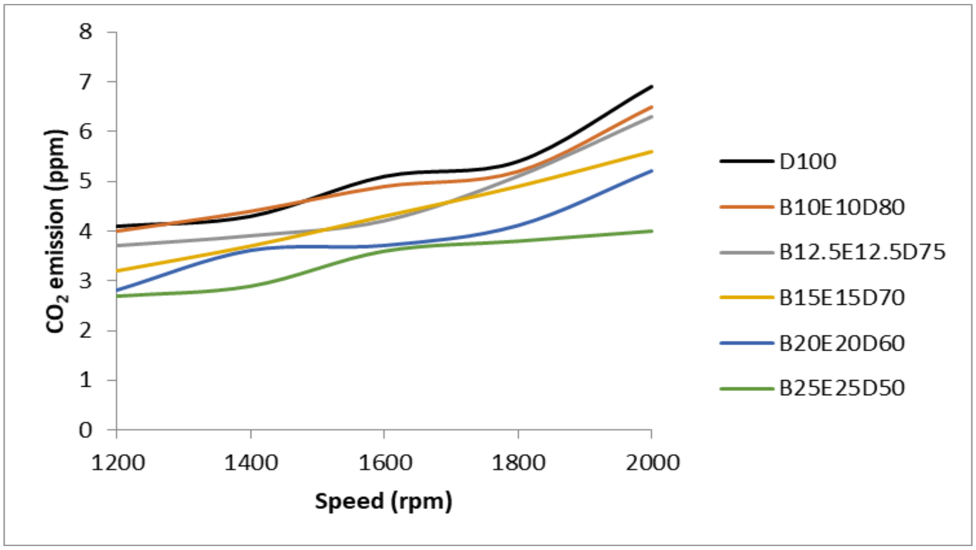


Figure 7: The variation of carbon dioxide emission with engine speed.

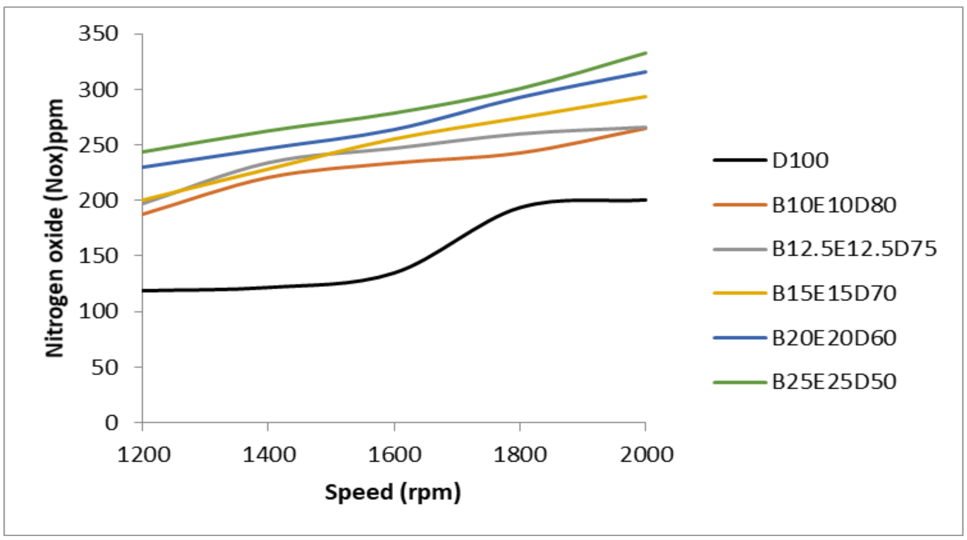


Figure 8: The variation of nitrogen oxide with engine speed.

## 4. Conclusion

This study presents experimental investigation of performance and emissions characteristics of a four stroke, four-cylinder diesel engine when using various biodiesel-ethanol-diesel blends compared against diesel as baseline fuel. Biodiesel was produced from crude Jatropha oil and blended with ethanol and diesel fuel at different blend ratios (B10E10D80, B12.5E12.5D75, B15E15D70, B20E20D60 and B25E25D50). The results show that the brake specific fuel consumption for biodiesel-ethanol-diesel blends is generally higher compared to diesel fuel. For B10E10D80 blend, BSFC is lower than that of diesel fuel for speed range less than 1500 rpm. The brake power output for all fuel blends is slightly lower than that for diesel fuel at the range of speeds investigated. The analysis of exhaust emissions shows that by increasing the biodiesel-ethanol ratio in the fuel blend $CO_2$ emission is decreased while NOx emission is increased when compared with diesel fuel for the entire range of engine speeds examined. Based on the present results, ethanol could be added to the diesel fuel in the presence of biodiesel to fuel a diesel engine and give a satisfactory performance. It is recommended that the use of diesel-biodiesel-ethanol blends in a diesel engine be investigated at different engine loads, and that more of the important performance parameters be analyzed.

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