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# Effects of bioethanol addition to the biodiesel-diesel fuel blend on diesel engine exhaust emissions

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**Abstract**

The transition of energy sources from fossil fuel to biofuel is becoming a major topic in the world towards renewable energy to reduce greenhouse gas emissions, improve environmental air quality, and reduce dependence on fossil fuel in the future. This study aims to evaluate the effect of increasing the concentration of oxygenated biofuel in diesel fuel on the emissions of diesel engines. In this study, B30 (30% biodiesel and 70% diesel) was used as a base fuel, and a fraction of pure biodiesel (B100) was added to increase the biodiesel concentration in B30 fuel to create B40 (40% biodiesel and 60% diesel). Furthermore, the addition of 5% and 10% of bioethanol as a fuel additive in the fuel blend was conducted while maintaining a biodiesel concentration of 40%. The effect of bioethanol contained in the fuel blends was tested using a single-cylinder 418 cc diesel engine. The experiment was carried out at an engine speed of 1000–3000 rpm. The result shows that the concentration of the diesel-biodiesel-bioethanol blend affected the emissions produced by the diesel engines. Combustion efficiency increased with the concentration of biodiesel in the diesel fuel, as shown by reduced CO emissions, increased CO2 emissions, and increased NOx emissions at engine speeds of 2000–3000 rpm. In comparison to 5% bioethanol at various engine speeds, adding 10% bioethanol has a disadvantageous effect on the combustion process, increasing CO and HC emissions.

**Keywords**: bioethanol, biodiesel, emission, $CO_2$, NOx

## 1 Introduction

Energy consumption rapidly increases every year as a result of population growth, industrialization, and the growth of the transportation sector, thereby increasing the exploration of fossil fuels [1]. This growth has prompted an increase in global fuel prices, the depletion of fossil fuel reserves, and an increase in poisonous gas emissions, raising concerns about the effects of future global warming and motivating scientists to create biodiesel fuel to restrict the use of fossil fuels [2].

One important factor in the use of biodiesel fuel in diesel engines is that it is technically acceptable and has high energy conversion efficiency. In an internal combustion engine, the process of converting thermal energy to mechanical energy is greatly influenced by the characteristics of the fuel used because the combustion reaction occurs at different pressures and temperatures for a certain duration. Researchers conducted studies to obtain biodiesel fuel from various natural sources to obtain the biodiesel properties that meet the standards of diesel engines by converting triglycerides to methyl ester, as has been done by Syam, *et al*. [3].

Biofuel has characteristics similar to diesel fuel, adding some fraction of biofuel to diesel can affect the fuel's properties, such as stability, density, viscosity, energy content, and cetane number [4]. Compared to pure diesel, biodiesel-diesel blended fuel has a higher viscosity, which affects fuel evaporation during the injection of fuel into the cylinder, resulting in an incomplete combustion process, lowering the conversion efficiency of diesel engines, and increasing emissions.

Therefore, the addition of other components is necessary to obtain the appropriate characteristics of standard fuel. Bioethanol has a lower viscosity compared to diesel and biodiesel, so the high viscosity of the biodiesel-diesel blends can be reduced by the presence of bioethanol. Meanwhile, the low cetane value of bioethanol could be balanced by the high cetane number of biodiesels. The solution of adding bioethanol is one way to bring the fuel properties of a biodiesel-diesel blend closer to those of diesel fuel. The addition of bioethanol is predicted to increase energy conversion efficiency, reduce emissions produced, and reduce dependence on fossil fuels so that the use of renewable energy as an energy source could be increased [5-7].

Ethanol is a low-chain alcohol that could be substituted in some fraction by being blended with diesel fuel to operate a compressed ignition engine [8]. Bioethanol has been widely used as a supplement in diesel engines and has a positive effect on engine performance [9]. This is due to bioethanol's 35% oxygen concentration, which allows for more complete combustion [10]. However, the presence of more than 8% ethanol (D92E8) in diesel fuel caused ignition delays and abnormal engine performance [11]. In addition, the biodiesel-bioethanol-diesel blend increases auto-ignition delay and combustion pressure and reduces CO and nitric oxides (NO*x*) emissions [12]. With the addition of ethanol, CO emissions were reduced by up to 43% or 2.4 g/kWh, and NO*x* emissions were reduced by 20% [13]. Besides some fractions of bioethanol being used in diesel engines, the experiments carried out on gasoline engines also had a positive effect on the emissions produced [14].

To improve energy conversion in diesel engines, Taghizadeh-Alisaraei and Rezaei-Asl [11] conducted a test in which it added 6% bioethanol to diesel fuel, which increased torque and power by an average of 8.3% compared to utilizing diesel fuel, as well as acceleration by 4.79%. Torres-Jimenez, et al. [15] recommended mixing ethanol up to 15% into an 85% concentration of diesel to increase the flash point and stability of the mixture. The concentration of 15% bioethanol was carried out by Sandalcı, *et al*. [16], which shows the decreased engine performance, but also decreased $CO_2$ and NO*x*. Power reduction was also obtained in testing the addition of 20% bioethanol as an additive to gasoline fuel [17].

In addition, testing of diesel engines was also carried out using a mixture of bioethanol with a concentration of 20% biodiesel to petroleum diesel, resulting in increased thermal efficiency at various fuel injection times. This is caused by the combustion process being more stable with the addition of bioethanol, which makes the characteristics of the biodiesel-diesel mixture closer to pure diesel in the presence of bioethanol concentrations [18]. Blending bioethanol with biodiesel reduces the viscosity and crystallization of biodiesel, making it an excellent solvent when mixing a higher fraction of biodiesel in diesel fuel [19]. Other advantages obtained from biodiesel and bioethanol are oxygenated fuels that have the potential to reduce CO emissions, due to the higher oxygen contents of biofuel [20].

The lower cetane number in bioethanol could be replaced with the high cetane number in biodiesel. The addition of bioethanol also used to prevent corrosion in high-pressure common-rail fuel systems [18]. Furthermore, bioethanol, biodiesel, and diesel blends could be combined at room temperature [21].

Diesel engine simulation using the virtual engine simulation performed by Praptijanto, et al. [10], adding 10% ethanol to diesel fuel. The experiment was done at engine speeds of 1000–1500 rpm and engine load up to 60 N.m. The results show that there was a decrease in soot, CO, and NO*x* emissions. Furthermore, investigations have been carried out to compare the addition of ethanol and methanol as additives to biodiesel-diesel blends. The specific fuel consumption attained with the addition of ethanol is better than that of methanol, and reduces NO emissions while increasing CO and HC emissions [22]. Emissions of CO and NO*x* are also reduced when 10% ethanol is used [4]. In experiment with an engine speed of 750 rpm and a engine load of 40 N.m, a concentration of 3% ethanol addition resulted in increase in cylinder pressure of up to 4.1% and a maximum heat release of 13.7% [23].

Recent studies have been conducted to optimize the use of biodiesel-diesel fuels, such as examining the effects on diesel engine components, energy conversion efficiency, and the production of biodiesel fuels. The addition of supplements to fuel from other natural sources is an effective method to improve energy conversion efficiency. However, the blending effect causes changes in fuel properties. Therefore, further analysis is needed to meet the fuel standard for diesel engines. The consequences of fuel blends on the engine components were studied, it was discovered that ethanol-biodiesel-diesel fuel mixes have similar effects on injection pump durability [12]. The effect on performance has also been carried out experimentally with the addition of biodiesel with concentrations of 10%, 20% ethanol, and 70% diesel blends, showing positive results. The thermal efficiency increases due to more stable combustion process compared to pure diesel fuel. The addition of ethanol to the biodiesel-diesel mixture resulted in the physical and chemical properties of the fuel blend approaching those of pure diesel fuel [18]. The fuel properties are shown in Table 1.

Table 1. Properties of fuels [4, 18]

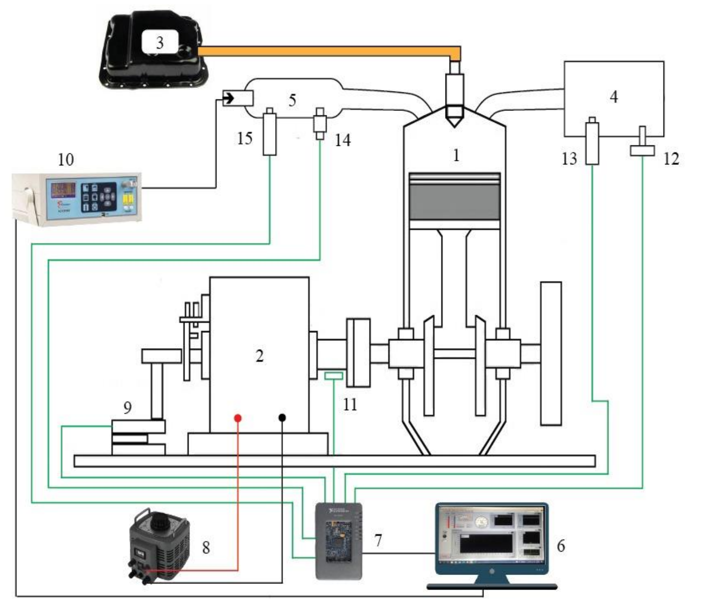
| Properties | Diesel | Biodiesel | Ethanol |
|---|---|---|---|
| Viscosity (@40 °C $mm^2/s$) | 4.127 | 7.159 | 1.13 |
| Low heating value (MJ/kg) | 43.61 | 37.69 | 26.78 |
| Oxygen content (% weight) | 0 | 11.1 | 34.75 |
| Latent heating (@25 °C kJ/kg) | 270 | 258 | 916 |
| Cetane number | 53 | 61 | 8 |
| Density (@20 °C $kg/m^3$) | 830.4 | 882 | 788 |
| Stoichiometric air/fuel ratio | 15 | 13 | 9 |

Increasing the concentration of biofuels in fossil fuels as a main energy source, such as bioethanol is a promising solution to reduce the use of fossil fuels, thus decreasing reliance on fossil fuels [24]. This study evaluated experimentally the effect of increasing the concentration of 40% biodiesel with the addition of bioethanol up to 10% on the exhaust emissions produced by using a direct injection diesel engine. As a result, increasing the concentration of biodiesel and bioethanol might lead to a decrease in diesel fuel consumption.

## 2 Research methods

### 2.1 Experimental Setup

This study was carried out using a standard laboratory diesel engine and a test equipment device integrated with a computer, which included a diesel engine, eddy current dynamometer, and gas analyzer, as shown in Fig. 1, and the specifications of the diesel engine used in this experiment are shown in Table 2.




Description:
1. Diesel Engine 2. Dynamometer 3. Fuel Tank 4. Intake 5. Exhaust 6. Computer 7. Ni My RIO 8. Load Control 9. Load Cell 10. Gas Analyzer 11. Speed Sensor 12. Pressure Sensor 13. Intake Temperature Sensor 14. Oxygen Sensor 15. Exhaust Temperature Sensor

Fig. 1. Schematic diagram of a diesel engine test bed

The experiments were carried out with four different fuel mixtures. To ensure normal engine operating conditions during each fuel test, real-time data measurements such as inlet and exhaust air temperature, inlet air pressure, air intake velocity, and fuel consumption are obtained from the sensors installed in the diesel engine. Data were recorded on a personal computer connected to the MyRio microcontroller through the LabView software interface and recorded with a data recording interval of 0.5 seconds.

Table 2. Engine Specification

| Parameters | Value |
|---|---|
| Engine Type/Model | 4 stroke, Vertical cylinder, direct-injection/186FA |
| Displacement | 418 cc |
| Bore x Stroke | 86 x 72 mm |
| Power Output | 6,3 kW @ 3600 Rpm |
| Mean speed of piston | 864 m/s @ 3600 Rpm |
| Mean effective Pressure | 502,4 kPa |
| Specific fuel consumption | ≤ 281,5 g/kW.h |
| Cylinder | *Single* cylinder |
| Fuel | Diesel |

Emission testing was carried out utilizing a standard fuel called Biosolar (B30) developed and marketed in Indonesia, with a concentration of 30% biodiesel and 70% diesel by volume fraction, a fraction of pure biodiesel (B100) was added to increase the biodiesel concentration in B30 fuel to create B40 (40% biodiesel and 60% diesel). The addition of 5% and 10% of bioethanol as a fuel additive in the fuel blend was conducted while maintaining a biodiesel concentration of 40%. The code of concentrations for each diesel-biodiesel-bioethanol fuel mixture used in this study is provided in Table 3. The concentration of diesel fuel could be reduced by increasing the concentration of pure bioethanol and biodiesel.

Table 3. Fuel codes and concentrations of mixture

| Fuel Code | Diesel (% vol) | Biodiesel (% vol) | Bioethanol (% vol) |
|---|---|---|---|
| B30 | 70 | 30 | 0 |
| B40E0 | 60 | 40 | 0 |
| B40E5 | 55 | 40 | 5 |
| B40E10 | 50 | 40 | 10 |

The addition of pure biodiesel (B100) to increase the biodiesel concentration in base fuel B30 to B40E0 (60% diesel + 40% biodiesel + 0% bioethanol) requires the addition of 14.29% B100. Meanwhile, to produce diesel-biodiesel-bioethanol blended fuel with a 5% bioethanol concentration in the standard B30 fuel, 16.43% B100 is needed to produce B40E5, and for a 10% bioethanol concentration, 18.57% B100 is needed to produce B40E10. The fuel properties of the diesel-biodiesel-bioethanol mixture are shown in Table 4.

Table 4. Properties of fuels mixture

| Properties | B30E0 | B40E0 | B40E5 | B40E10 |
|---|---|---|---|---|
| Viscosity (@40 °C mm$^2$/s) | 5.03 | 5.34 | 5.19 | 5.04 |
| Low heating value (MJ/kg) | 41.83 | 41.24 | 40.40 | 39.56 |
| Carbon content (% mass) | 83.22 | 81.85 | 81.25 | 80.62 |
| Hydrogen content (% mass) | 12.19 | 12.27 | 12.30 | 12.33 |
| Oxygen content (% mass) | 4.59 | 5.88 | 6.45 | 7.06 |
| Latent heating (@25°C kJ/kg) | 266.4 | 265.2 | 297.2 | 329.8 |
| Cetane number | 51.9 | 53.2 | 51.2 | 49.2 |
| Density (@20 °C kg/m$^3$) | 845.8 | 851 | 848.9 | 846.8 |
| Stoichiometric air/fuel ratio | 13.47 | 13.29 | 13.20 | 13.11 |

A gas analyzer was used to measure exhaust emissions from a diesel engine running on various fuel blends. The data from the variable fuel mixture test is recorded on a computer. The parameters of the emission sensors used are described in Table 5.

Table 5. Parameter sensors of gas analyzer

| Sensor | Range | Resolution |
|---|---|---|
| Carbon Monoxide (CO) | 0-8000 ppm | 1 ppm |
| Carbon dioxide ($CO_2$) | 0.0% - 16.0% | 0.1% |
| Nitric Oxide (NO) | 0-4000 ppm | 1 ppm |
| Nitrogen Dioxide ($NO_2$) | 0-1000 ppm | 1 ppm |
| Sulfur Dioxide ($SO_2$) | 0-4000 ppm | 1 ppm |
| Hydrocarbons (HC) | 0-0.40 % | 0.01 % |
| Stack Gas Flow Rate | 0 – 65000 cfm | 1 cfm |

Emissions produced by each fuel were measured at engine speeds of 1000–3000 rpm with an interval of 500 rpm. The engine speed remained constant for 5 minutes to ensure accurate results for each fuel test. To obtain reliable results from each emission sample tested, the gas analyzer is first autozero calibrated using the calibration menu offered on the gas analyzer.

### 2.2 Data Analysis

The emission result from all fuel mixtures with variations of engine rotation speed by 1000-3000 rpm was evaluated including Carbon Monoxide (CO), Carbon dioxide ($CO_2$), Nitric Oxide (NO), Nitrogen Dioxide ($NO_2$), and hydrocarbons (HC). The analyzed data using an average value that measured stability for each variation of fuels and engine speed.

## 3 Results and Discussion

Fig. 2 shows the effect of diesel-biodiesel-bioethanol blended fuels on carbon monoxide emissions at various blends. Carbon monoxide increased with increasing biodiesel and bioethanol concentrations. The average increase in the CO of B40E0 fuel occurred at low rotation speeds around 1000–1500 rpm with 28.8%, due to the increased viscosity of the fuel, which inhibits vaporization during the fuel injection process into the cylinder, as well as lower turbulence of the air in the cylinder during the combustion process, and the decreasing CO emission accrued at engine speeds of 2000–3000 rpm, which closed to B30 standard fuel.

Whereas the addition of bioethanol at 5% and 10% results in an increase in CO concentration at varied engine speeds due to the lower combustion reaction temperature induced by bioethanol's high latent heat [4]. The high latent heat reduced the oxidation rate of CO to $CO_2$ [25].

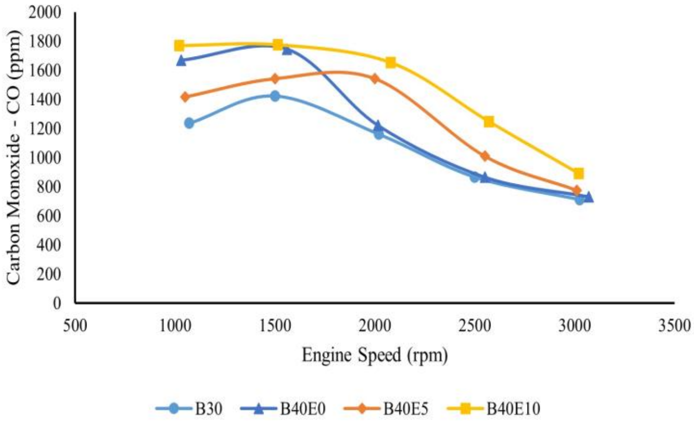



Fig. 2. Effect of biodiesel and bioethanol concentrations on CO emissions at various engine speeds.

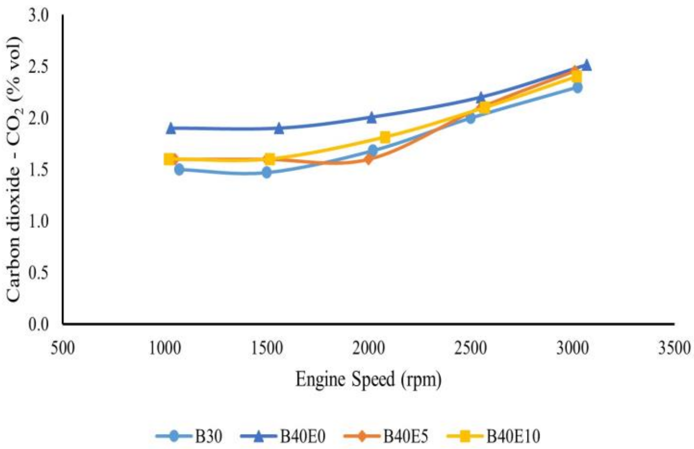



Fig. 3. Effect of biodiesel and bioethanol concentrations on $CO_2$ emissions at various engine speeds.

The increased CO is also caused by the low cetane number of bioethanol. The high concentration of bioethanol reduced the cetane number of the blended fuel, thereby increasing the ignition delay, which could potentially lead to incomplete combustion. In addition, the CO emission production rate is also affected by the air-fuel ratio and engine rotation speed [4]. An increased CO due to the addition of bioethanol to diesel-biodiesel blends was also observed in a previous experiment with 20% biodiesel and 5% ethanol conducted by Randazzo and Sodré [25]. At idle engine speed, the experiment with the addition of up to 10% ethanol conducted by Kim, *et al*. [23] showed increased CO concentration by increasing ethanol concentration up to 13.5% at 5% ethanol concentration and 27.4% at 10% ethanol concentration.

The high conversion rate of CO to $CO_2$ resulted in a high formation of $CO_2$ and a decrease in CO, which indicates a better combustion reaction [26]. Fig. 3 shows the increase in $CO_2$ is proportional to the decrease in CO at higher engine speeds. The average increase in $CO_2$ emissions at various engine speeds by using B30 and B40 fuel is 1.96% and 2.26%, respectively. $CO_2$ emissions decrease with the addition of ethanol in the fuel blends due to the addition of bioethanol decreasing the C/H ratio and increasing the oxygen concentration, as shown in Table 4. However, increasing the biodiesel concentration results in higher $CO_2$ at various engine speeds due to the higher oxygen concentration in the fuel, which causes an increase in the conversion of CO to $CO_2$.

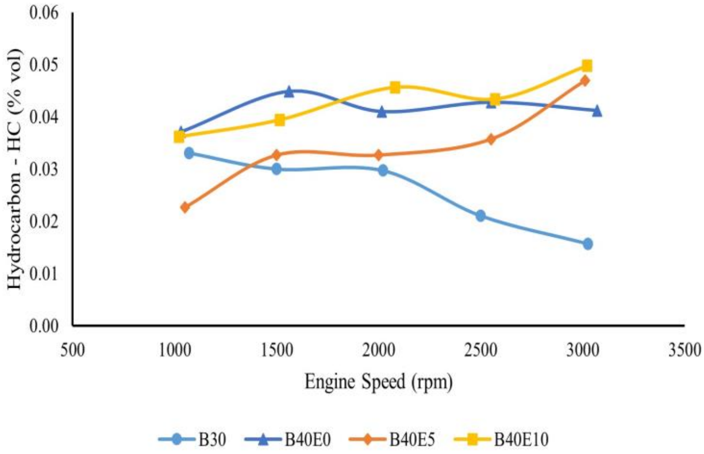



Fig. 4. Effect of increasing biodiesel and bioethanol concentrations on HC emissions at various engine speeds.

Fig. 4 shows a significant decrease in hydrocarbon (HC) emissions with the addition of bioethanol in the Biodiesel-Diesel blend fuel. The addition of 5% bioethanol, or B40E5, obtained an average decrease of 21.44% compared to B40E0 at engine speeds of 1500–2500 rpm, indicating a more complete combustion process of B40E5 fuel compared to B40E0. The higher latent heat of bioethanol compared to biodiesel increases the time for fuel vaporization, thus increasing the ignition delay of the blended fuel. In addition, ignition delay is also affected by the low cetane number of the blended fuel [27]. Hence, there is an increase in HC emissions at 10% bioethanol concentration or B40E10, the HC produced was close to B40E0 fuel. The high HC emission of B40E0 fuel is due to the high viscosity of the fuel, which affects the fuel spray vaporization and inhibits the combustion reaction.

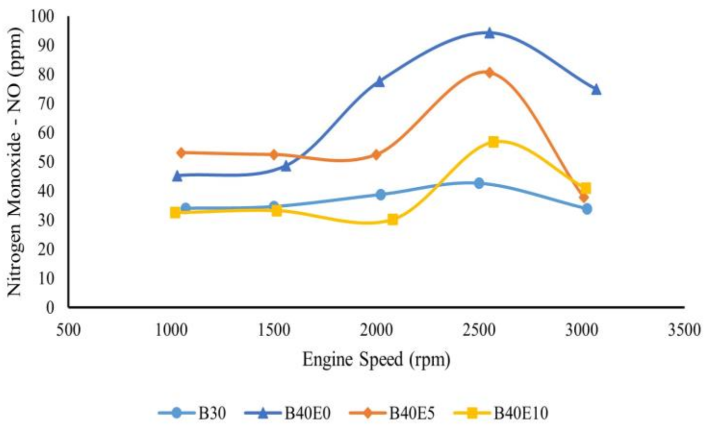



Fig. 5. Effect of adding biodiesel and bioethanol concentrations on NO emissions at various engine speeds.

Nitrogen monoxide (NO) emission is a process of oxidation to nitrogen dioxide ($NO_2$) produced during high-temperature combustion reactions. The sum of NO and $NO_2$ is called NO*x* (NO + $NO_2$) [28]. Fig. 5 shows NO emissions, and Fig. 6 shows NO*x* emissions. Both Fig.s show the same profile. The high cylinder temperature during the combustion process occurs in B40E0, which has the highest NO and NO*x* concentrations compared to the three other fuels mixture. Increasing the cetane number with increasing biodiesel concentration could be reduced ignition delay and increase combustion efficiency, which results in an increase in cylinder temperature during the combustion process, which forms higher NO*x*. An increase in NO*x* due to an increase in biodiesel concentration was also obtained in tests of up to 20% conducted by Randazzo and Sodré [25].

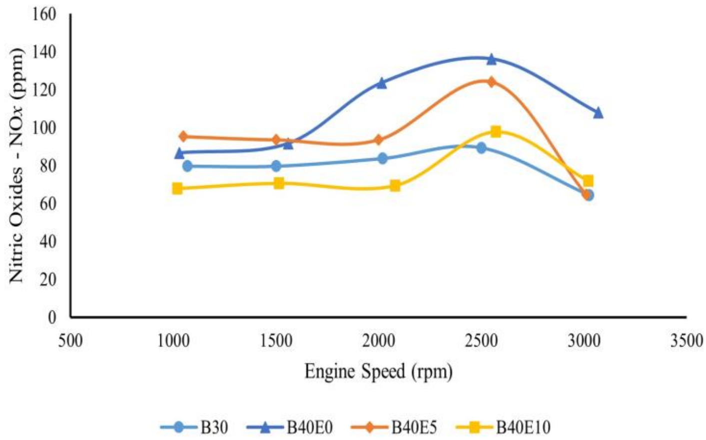



Fig. 6. Effect of biodiesel and bioethanol concentrations on NO*x* emissions at various engine speeds.

The addition of bioethanol increases the ignition delay in the combustion process, thereby reducing cylinder temperature and pressure, which results in a decrease in NO and NO*x* emissions. The average decrease in B40E10 was 14.48%, while the addition of 5% bioethanol increased NO*x* up to 16.23% at 1000-2000 rpm compared to the standard B30 fuel. The decreased NO*x* emissions with the addition of 10% bioethanol was also obtained in the study of Rakopoulos, et al. [27]. In addition, a 6.9% reduction in NO*x* emissions was obtained in the test of adding 10% ethanol to diesel fuel by Kim, *et al*. [23].

## 4 Conclusions

Experimental studies were conducted using diesel-biodiesel-bioethanol blended fuel on a single-cylinder diesel engine with various engine speeds. Based on the experimental study, it is concluded that increasing the concentration of biodiesel from 30% to 40% in diesel fuel increased the oxidation of CO to $CO_2$, indicating a combustion process closer to stoichiometry due to the increased oxygen molecular content in the fuel. This phenomenon increases the NO*x* produced due to the combustion process occurring at high temperatures. The addition of bioethanol increased CO and HC emissions compared to standard fuel with a 30% biodiesel concentration at various engine speeds due to the limited time to complete the combustion process. The higher bioethanol concentration increased the latent heat of the fuel mixture, which caused the combustion reaction temperature to decrease, resulting in lower NOx emissions, and increased HC emissions caused by increasing the time for fuel vaporization, thus increasing the ignition delay of the fuel mixture.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