Optimization of Indicators Pollutant Emission Following Blending Diesel Fuel with Waste Oil-Derived Biodiesel

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Abstract: The growing global demand for fossil fuels and considerable environmental threats and risks have prompted researchers to launch investigations over some renewable energy sources in recent years. Especially biodiesel and ethanol have been considered as major alternative fuels as they are derived from renewable resources. These fuels are well oxygenated and therefore have a great potential to reduce emissions. Biodiesel, which is chemically derived from edible oils or animal fats by transesterification reaction, is esters of long-chain saturated/unsaturated fatty acids and can be an important alternative fuel source to consider for the vehicle. It can offer desirable features to diesel engines, and internal combustion engines (ICEs) in particular. The present study aims at determining and assessing the effect of the engine’s load and speed as well as various ratios of diesel and biodiesel fuels blending on the emissions of pollutants from the OM 314 diesel engine. Design Expert 11 statistical software was used. Second-order models obtained using response surface methodology (RSM) to predict the effect of input variables on response surfaces were statistically significant at an alpha level of 1. Following an increase in the percentage of biodiesel compared to pure diesel fuel, the HC (Hydrocarbons) emission rate decreased. According to the optimization results, the lowest HC emission rate (33.52 ppm), and the least NOₓ emission rate occurs when using 8.82% biodiesel. The lowest HC emission rate was observed after using pure biodiesel fuel. Following an increase in the percentage of biodiesel in the blended fuel, the NOₓ emission rate increased, while the lowest emission rate was observed after using pure diesel fuel. Engine smoke flow rate decreased after increasing the percentages of biodiesel in blended fuel compared to diesel fuel. A higher percentage of biodiesel was considered as the most effective way to reduce the rate of smoke opacity. According to the multi-objective optimization (MOO) results, the lowest HC, and NOₓ emission rates and the rate of smoke opacity was observed for blended fuel “D32.47B67.53” with the Desirability of 60% under applying a load of 41.36% and rotational speed of 1383 rpm.

Key words: biodiesel, pollution characteristics HC, NOₓ, smoke opacity, engine performance, response surface

1 Introduction

Developing alternative fuels have gained considerable media attention in recent years because they can decrease the dependence on non-renewable and expensive fossil fuels, besides helping to improve air quality¹⁻³. The automotive industry has attempted to devote all its resources with the aim of achieving the requirements of standard emission reductions derived from their vehicles. Emission reduction from the combustion engine is focused to reduce environmental problems and air pollution⁴. In this aspect, the use of sustainable fuel alternatives such as alcohol, natural gas and biodiesel is the best way to reduce NOₓ, CO, HC, CO₂ emissions⁵⁻⁶.

Biodiesel is more prominent than other alternative fuels, and biodiesel production can be refined from various vegetable oils; for example, cotton seeds, soybeans, sunflowers, peanuts, palm oil and rapeseeds. Biodiesel has been widely used for combustion engines, especially in heavy-duty vehicles and marine engines⁷⁻⁹. The organic substances contained in biodiesel have high molecules such as alcohol, ketones, phenols and ether¹⁰. Biodiesel has a lower density than water. It can be stored for a longer duration in a stable
Biodiesel does not have aromatic hydrocarbons, and the sulfur content is lower than diesel. Thus, emissions from the production of biodiesel do not endanger human health and are also more environmentally friendly. Moreover, biodiesel has a lower amount of cetane than diesel fuel which further improves engine combustion performance

Shirmeshan et al. (2016) investigated the use of artificial bee cloning algorithm to optimize engine performance and fuel mix properties (biodiesel and diesel), engine speed, and engine load. The optimization results showed that the percentage of biodiesel, engine speed and load were 85.63%, 2208 rpm and 97%, respectively. At the optimum point, the values of power, torque, BSFC, CO, HC and NOX were 63 kW, 298 Nm, 202.85 g/k, 0.012%, 88 ppm and 560 ppm, respectively. This finding proves that this algorithm can accurately estimate the optimal point in engine performance

Helwani et al. (2009) studied technologies for the production of biodiesel focusing on green catalysis techniques. They reported that after burning pure biodiesel, the carbon monoxide (CO) emission rate is reduced to 46.7%. The emission of particulate matters (PMs) and unburned hydrocarbons (UHC) also is decreased by 66.7% and 45.2%, respectively. Biodiesel is non-toxic, and therefore suitable for transportation in sensitive environments such as marine ecosystems or areas that are contaminated with land mines. Compared to conventional diesel fuel, the oxygen content of the biodiesel improves its combustion characteristics. The content of MPs, CO and total hydrocarbons (THC) is therefore reduced in the ICEs, while the content of nitrous oxide (NOX) is increased.

The results of research conducted by the Environmental Protection Agency of the United States (US EPA) on materials emissions in heavy-duty diesel engines (a case study of a B20 biodiesel engine; the biodiesel volume percent of 20%) showed that CO, HC, and MP contents is decreased by 13, 20, and 20%, respectively, while the average NOX emission rate is increased by 4%; these results are consistent with the findings of the study conducted by Lapuerta et al. (2008). An increase in NOX emission rate after using biodiesel application may be, therefore, a constraint to the use of this fuel. There are, however, debates on the NOX emission rate in other researches. The results of the study conducted by Rakopoulos et al. (2006) demonstrate a slight decrease in the NOX emission rates.

Najafi et al. (2016) tested different percentages of biodiesel blending from sunflower oil on a dual-burner diesel engine using the RSM method. They concluded that CO, NOX and UHC (unburned hydrocarbons) emissions in pure biodiesel fuel were reduced by 67, 8 and 2%, respectively, compared to the use of pure diesel fuel. Also by adding 10 to 20% biodiesel to the pure diesel, the engine power was almost maintained, but the emission of pollutants decreased

### 1.1 Pollution Meter Instruments

The AVL DiGas 4000 pollution meter was used to measure the pollutant emission rate. It can measure the NOX (NO and NO2) emission rate in ppm using a chemiluminescent detector. A nondispersive infrared sensor (or NDIR sensor) was used to measure the CO and CO2 emission rates (in gas volume percentage) and HC (in ppm).

The AVL DiSmoke 4000 was used to measure opacity, where the smoke opacity level was determined in percent (from 0 to 100) and with an accuracy of ±0.1 using a part-flow smoke opacimeter.

During the tests and for each fuel mixture, the inlet pipe of each pollutant meter instrument is sequentially connected to the test engine’s exhaust. The values displayed on the screen for various pollutants are then recorded. Table 1 presents the accuracy and range of measurement of various pollutants by the aforementioned pollutant meter instruments.

### 2 Methodology

In other studies, the percentage of mixing has been performed on several specified levels e.g. (0, 20, 50, 80, 100) but in this study the mixing has been continuously studied from 0 to 100, and we have also modeled the pollution.

Short-term tests were conducted on various diesel and biodiesel fuel blending, aiming to provide the output pollutants’ parameters. The load applied by the dynamometer to the engine, engine speed and fuel type (different diesel-biodiesel blending) were considered as control variables. Concentrations of HC and NOX and smoke opacity rate were measured using a pollutant meter instrument. The engine’s outlet and inlet water temperatures, the smoke temperature, the test cell temperature, and the oil pressure were also observable by the computer installed in the testing unit at the control room.

The two major designs presented here includes the Central Composite Design ( CCD) and the Box-Behnken Design (BBD). The CCD design is obtained by adding axial and multi-center points to the factorial design, where the
The number of experiments is calculated as \(2^k\), in which \(k\) is the number of parameters.

The CCD design will be rotatable, with the correct selection of the parameter \(\alpha\) (level of a factor) for the central points, where five levels are determined for each variable. The levels specified, indeed, are defined from \((\alpha)\) to \((-\alpha)\), where the minimum and maximum limits are denoted by the level code of \((0)\) and \((-1)\), respectively, and the fifth level is considered as the central level or zero \((0)\). The CCD design used in this study is most commonly used among response surface methodology designs\(^{22}\). The independent variables are different ratios of biodiesel and diesel fuels, engine’s load and speed, and optimal responses including pollutant emissions and specific fuel costs. Based on the CCD design, the levels of the independent variables are chosen based on the coded values of 0, \(\pm 1\), \(\pm \alpha\), where \(\alpha\) is the squared number of independent variables\(^{21}\).

The minimum and maximum values in the experiment for each variable correspond to the codes of \(\pm 1\); using the equations 1, the other coded values \((0\) and \(\pm \alpha)\) will be obtained.

\[
x = \frac{x - x_{\text{ave}}}{\Delta x}
\]

(1)

Therefore, the response level method (as one of the experimental design methods) was used in this study. When designing experiment, according to the following relationship (where \(x_1, x_2, x_3, \ldots\) are the different parameters, \(\xi\) is the statistical error \([\text{derived from other sources}]\) and \(y\) is the output), the aim is to make some changes in the output by changing the values of the parameters. Then, using the data analysis methods of the experiment, the effect of each parameter is assessed and the output is predicted for the new parameter values and the process is optimized if needed\(^{21}\).

\[
y = f(x_1, x_2, x_3, \ldots) + \xi
\]

(2)

The equation for the model that will be derived from the implemented plan is as follows for each answer.

\[
y = a_0 + \sum_{i=1} a_i x_i + \sum_{i=1} \sum_{j=1} a_{ij} x_i x_j
\]

(3)

2.1 Determination of engine exhaust emission characteristics

The emission characteristics of the engine consisted of the emission of HC, NO\(_X\), and smoke opacity which were analyzed by design expert 11 software. For each characteristic, the mathematical model was obtained, based on independent variables including the percentage of biodiesel, and engine’s speed and load; the validity of this model was evaluated using ANOVA and regression analysis.

2.2 Development of a mathematical model for HC characteristics and its validation

Generally, HC emission increases due to the wet wall, insufficient oxygen, and residual (sedimentation) fuel. HC is also the result of incomplete combustion of fuel and cooling or shut downing\(^{23,24}\).

In the ANOVA table, the \(p\) value for the prediction model is less than 0.01, indicating that the model is statistically capable of predicting the effects of independent variables on the HC emission rate. The linear, second-order, and reciprocal expressions of the HC emission model having a \(p\) value of less than 0.05 are statistically validated and can use in the model. According to Table 2, biodiesel linear expressions, the engine’s speed, and load have a significant effect on the HC emission rate and are included in the model. The \(p\) value of all second-order expressions is less than 1\%, so they can well predict the second-order effects of the independent variables on the dependent variable and are included in the prediction model. Among the reciprocal expressions, there is a significant association between the engine’s load and speed at the 5\% level, and so this expression is also included in the model. The coefficients of second-order expressions of biodiesel, and the engine’s

| Table 2 | Analysis of variance (ANOVA) for expressions of the HC emission model. |
|---------|---------------------------------------------------------------------------------------------------------------|
| Source  | DF | Coefficient | Sum of squares | Mean squares | F  | P value |
| Model   | 6  |              | 996.29         | 333.10       | 8.84 | 0.0011   |
| Linear expression | 3 | -11.44 | 968.83 | 322.94 | 25.70 | 0.0001 |
| Speed   | 1  | -12.07      | 173.82         | 173.82       | 4.63 | 0.047    |
| Load    | 1  | -22.94      | 633.01         | 633.01       | 16.85 | 0.0008   |
| Biodiesel | 2 |           | 534.85         | 178.28       |     |          |
| Interaction | 1 | 66.19 | 22.06 | 0.53 | 0.046 |
| Speed \(\times\) Load | 1 | -16.28 | 66.3 | 66.3 | 5.28 | 0.04 |
| Error   | 16 |            | 601.05         | 37.57        |     |          |
| Total   | 19 |            | 1597.34        |             |     |          |

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speed and load are positive, indicating that these expressions have a positive effect on the HC emission rate so that an increase in each of these expressions will increase the HC emission rate.

The coefficient of determination of the model predicting the HC emission rate and the constant value of the model coded were 62.37% and 44.32, respectively. The equation of the model predicting HC emission rate model is based on real (non-coded) numbers, where HC represents the emission of hydrocarbons in ppm, B denotes the biodiesel’s volumetric ratio in the fuel mixture, S is the engine’s speed in rpm, and L is the engine’s load (%).

\[ HC = 123.8 - 0.0276S + 0.899L - 0.475B + 0.00009S^2 + 0.00082L^2 + 0.00246B^2 - 0.000226SL \] (4)

2.2.1 Effect(s) of load and speed on the HC emission rate in fuel (Fig. 1)

Under low loads and speed, the formation of unburned or semi-burned hydrocarbons is facilitated, due to insufficient fuel distribution in combustion chamber, higher oxygen to fuel ratios in some points of the combustion, as well as lower temperature of the combustion chamber, all resulting in increased HC emissions rate for all fuel mixtures; but at higher speeds and for different mixes, the fuel in the combustion chamber is better atomized as the engine load increases, due to increased injection pressure as well as increased Inlet air flow rate; this creates a homogeneous mixture of fuel and air, resulting in reduced HC emission rate. In other words, the main cause of the decrease in HC emissions rate at the higher engine’s speeds is the increase in the coefficient of fuel atomization\(^{24,25}\). At higher loads and speeds, the hydrocarbons emission rate increases somewhat due to insufficient time to establish a proper combustion process.

2.2.2 Effect(s) of the biodiesel on the HC emission rate in fuel (Fig. 2)

As the percentage of biodiesel increases, the rate of HC emission will be decreased; this may be due to the increase in biodiesel content in the blended fuel, which increases the oxygen content in the fuel and improves the combustion process, resulting in a decrease in the amount of HC emission rate. On the other hand, the higher cetane number of biodiesel diminishes the delay rate in the ignition process; this leads to better combustion and thus reduces the HC emission rate\(^{26,27}\). The slight increase in the HC emission rate at higher volumes of biodiesel may be due to the increased viscosity of biodiesel at these values, making it difficult to atomize the fuel. On the other hand, low volatility of biodiesel as well can be effective at high biodiesel levels\(^{28}\).

2.2.3 Optimization of the HC emission rate for biodiesel percentage, and the engine’s speed and load

According to the optimization results, the lowest HC emission rate (33.52 ppm) occurs under the applied load of 95.77%, the rotational speed of 1837 rpm and when using 95.76 biodiesel fuel. The highest HC emission rate (64.16 ppm) also occurs under the applied load of 33.43%, the rotational speed of 1409 rpm, and when using 15.80% biodiesel.

2.3 Development of a mathematical model for NO\(_x\) characteristics and its validation

NO\(_x\) is the most harmful pollutant in internal combustion

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Fig. 1 Three-dimensional illustration of the effects of the engine’s load and speed on the HC emission rate in B\(_{50}\) fuel.

Fig. 2 Three-dimensional illustration of the effects of the biodiesel content on the HC emission rate at various speeds and loads.
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There is no significant relationship between other expressions and the dependent variable is included in the model. While on the other hand, first-order and second-order sentences and their interactions with a $p$ value less than 0.05 are also statistically valid for including the equation; the model is therefore statistically validated.

The results show that linear factors biodiesel and the engine’s speed and load have a significant effect on NOX emission rate; there is a linear relationship between all linear expressions and the dependent variable (NOX emission rate). Second-order expressions "velocity" and "load" are significant at the 1% level, so they are included in the prediction model. On the other hand, according to the coefficients, there is a negative association between these expressions and the NOX emission rate. Among the reciprocal expressions (coefficients between two variables), the "speed × load" expression that has a direct relationship with the dependent variable is included in the model. While there is no significant relationship between other expressions and the NOX emission rate and so they will not be included in the model. A high value of $R^2$ (98.17%) indicates that there is a high correlation between observed and predicted values of the NOX emission rate. It also indicates that the proposed model can account for and predict 98.17% of total changes in the NOX emission under test conditions. The model obtained based on the non-coded data is as follow:

$$\text{NO}_X = -977.6 + 0.9621S + 7.42L + 1.082B - 0.000223S^2 - 0.041L^2 + 0.001315SL$$

Where NOX is the nitrogen oxides emission in ppm, B denotes the percentage of biodiesel in the fuel mixture, S is the engine’s speed in rpm, and L is the engine’s load in percentage. The positive sign of the coefficients indicates that the expression has a direct effect on NOX emission rate, while the negative sign indicates a negative effect on NOX emission rate. The constant value of the prediction model based on the design coded is 545.03 for NOX.

2.3.1 Effect(s) of load and speed on the NOX emission rate in fuel

In general, as the engine load increases, the fuel-to-air ratio in the combustion chamber increases, which raises the mean temperature of the combustion chamber resulting in increased NOX emission rate. According to Fig. 3, the NOX emission rate increases as the load increases due to an increase in the combustion chamber temperature. Also, with increasing the engine’s speed and under different loads, the NOX emission rate is increased first and then decreased at higher speeds. An increase in the engine’s speed will lead to an increase in the combustion gas temperature; this can accelerate the NOX emission rate at low and medium speeds. But at higher speeds, the mixing of fuel and air will occur faster and the combustion gas flowing is accelerated. As a result, the duration of the fuel-air reaction in each cycle of the engine decreases and the combustion gas remains in its maximum temperature for a shorter time; this prevents complete combustion and so the temperature of the combustion chamber is reduced to some extent. Therefore, the NOX emission rate is reduced at higher engine speeds for all fuel mixtures and loads.

| Source               | DF | Coefficient | Sum of squares | Mean squares | F     | P value |
|----------------------|----|-------------|----------------|--------------|-------|---------|
| Model                | 6  | 417800      | 69633.08       | 198.01       | 0.0001|
| Linear expression    | 3  | 353700      | 11790          | 29.34        | 0.0001|
| Speed                | 1  | 174.39      | 146600         | 146600       | 410.19| 0.0001 |
| Load                 | 1  | 199.94      | 193000         | 193000       | 548.8 | 0.0001 |
| Biodiesel            | 1  | 54.10       | 14131.79       | 14131.79     | 40.29 | 0.0001 |
| Second-order expression | 2  | 64046       | 32023          | 91.22        | 0.0001|
| Speed × Speed        | 1  | -178.0      | 57757.19       | 57757.19     | 169.76| 0.0001 |
| Load × Load          | 1  | -63.2       | 7829           | 7829         | 22.3  | 0.0001 |
| Interaction          | 1  | 2240.02     | 2240.02        | 2240.02      | 6.38  | 0.025  |
| Speed × Load         | 1  | 47.34       | 2240.02        | 2240.02      | 6.38  | 0.025  |
| Error                | 13 | 253.46      | 19.50          |              |       |        |
| Total                | 19 | 418100      |                |              |       |        |
2.3.2 Effect(s) of the biodiesel on the NO\textsubscript{x} emission rate in blended fuel

According to Fig. 4, as the percentage of biodiesel in the blended fuel increases, the NO\textsubscript{x} emission rate increases, due to the improvement of combustion efficiency by the presence of oxygen in the biodiesel fuel, which increases the combustion temperature and consequently the NO\textsubscript{x} emission rate. On the other hand, at a greater biodiesel’s cetane number compared to diesel fuel, the delay in the ignition will be diminished, and so the combustion period and temperature increased\textsuperscript{30}.

2.3.3 Optimization of the NO\textsubscript{x} emission rate for biodiesel percentage, and the engine’s speed and load

According to the optimization results and the response surface method, the least NO\textsubscript{x} emission rate occurs when using 8.82\% biodiesel, at rotational speed of 1560 rpm and under applying 20.13\% load; while the highest NO\textsubscript{x} emission rate (757.98 ppm) is achieved under the rotational speed of 2467 rpm, an applied load of 94.24\%, and when using pure biodiesel fuel.

2.4 Development of a mathematical model for smoke opacity characteristics and its validation

Particulate matters (PMs) are mainly composed of soot and some hydrocarbons, and generally refers to the percentage of the soluble organic fraction (SOF) of microparticles that are absorbed onto the surface of the particles. Soot is the most important cause of opacity. The $F$ value was calculated to be 76.56 in ANOVA and predicting smoke opacity level. The $p$ value for the prediction model was lower than 0.01, indicating that the model has statistically the capability to predict the effects of independent variables on the level of smoke opacity at the 1\% level. The first-order and second-order expressions, and overall model interactions were also statistically significant at the 1\% level and thus can be included in the prediction equation (Table 4).

The $p$ value of all first-order expressions is less than 0.01 and can statistically be included in the prediction model and to justify changes in the level of smoke production, so that, except the engine’s load, all other first-order variables (biodiesel and the engine’s speed) are inversely related to the smoke opacity. All second-order expressions were significant at the 0.01 level and were directly related to the smoke opacity and can, therefore, be included in the prediction model.

Among reciprocal expressions, the “speed $\times$ load” can be included in the prediction model. The rest of the expressions are not statistically significant and cannot justify the dependent variable changes; so they don’t include in the prediction model. The $R^2$ and adjusted $R^2$ values for the prediction model were 89.66 and 94.54\%, respectively. The following equation is related to the model predicting smoke opacity rate based on real numbers (non-coded) where SO represents the smoke opacity rate (\%), B denotes the percentage of biodiesel in the fuel mixture, S is the engine’s speed in rpm and L is the engine’s load (\%). The constant value of the prediction model based on the coded design is 8.728.

\[
SO = 72.3181 - 69.69048E - 169.2976E - 0.091757S + 0.075685L + 43.93601S^2 + 79.3755E + 285.7444E^2 + 0.000029S^2 - 0.0000442SL + 0.0098L^2
\] (6)
2.4.1 Effect(s) of load and speed on the smoke opacity rate in fuel

Smoke opacity is mainly due to oxygen deficiency. Air and oxygen deficiencies occur locally in diesel engines; the opacity rate decreases as the air-to-fuel ratio increases. Under oxygen deficiency, soot is produced to break down long-chain molecules\(^{31}\). Elevated combustion temperatures are also contributing factors to increased smoke levels at higher engine loads. As the temperature of the combustion chamber increases, the impact of the molecules increases, thus the level of smoke produced increased. Reducing fuel oxidation and increasing the accumulation of fuel particles are also influential factors that play roles in the next step, where an increase in the fuel-to-air ratio will decrease the oxidation of the fuel and increase the accumulation of vaporized fuel particles in parts of the combustion chamber, all leads the smoke level to eventually be increased. According to Fig. 5, the amount of smoke opacity increases with increasing load at low and medium speeds, due to the higher temperature of the combustion chamber, higher fuel-to-air ratio at higher loads that causing oxygen depletion in parts of the combustion chamber\(^{31, 32}\). But at higher speeds and under increased load, the smoke opacity level first decreases and then increases. Under lower loads, and as the velocity increases, the smoke opacity level decreases first and then increases; this may be due to the fact that at lower loads, as the velocity increases, the air-to-fuel ratio increases, while at high speeds, high values of spraying result.

In fuel-rich diffusion in the combustion chamber. Therefore, due to insufficient oxygen and low fuel oxidation, the smoke opacity rate increases. Also, under these conditions, increasing temperature increases the level of smoke produced\(^{30}\). But at higher loads, as the speed increases, the air-to-fuel ratio increases, resulting in increased fuel oxidation and reduced smoke opacity rate\(^{30}\). There is no significant relationship between the engine’s speed and load and the fuels tested; the process described is therefore qualitatively applicable to all fuel mixes.

2.4.2 Effect(s) of the biodiesel on the smoke opacity rate in fuel

As depicted in Fig. 6, as the percentage of biodiesel increases, the smoke opacity rate decreases at all speeds. Since the elements oxygen, carbon and sulfur exist in the molecular structure of fuels considerably affect the production of smoke and fuel oxidation process, the decrease can be attributed to the presence of oxygen molecules and the low content of carbon and sulfur in the molecular structure of biodiesel and fuel mixtures having biodiesel, which causes more fuel oxidation, and complete and more stable combustion process\(^{30}\).

**Table 4**  Analysis of variance (ANOVA) for expressions of the smoke opacity model.

| Source              | DF | Coefficient | Sum of squares | Mean squares | F      | P value |
|---------------------|----|-------------|----------------|--------------|--------|---------|
| Model               | 7  |             | 3346.81        | 478.12       | 76.65  | 0.0001  |
| Linear expression   | 3  |             | 2706.97        | 902.32       | 144.66 | 0.0001  |
| Speed               | 1  | -17.86      | 384.92         | 384.92       | 61.71  | 0.0001  |
| Load                | 1  | 26.50       | 847.55         | 847.55       | 135.87 | 0.0001  |
| Biodiesel           | 1  | -34.95      | 1474.51        | 1474.51      | 236.39 | 0.0001  |
| Second-order expression | 3 |             | 387.88         | 129.29       | 20.73  | 0.0001  |
| Interaction         | 1  |             | 251.96         | 251.96       | 40.39  | 0.0001  |
| Speed × Load        | 1  | -31.75      | 251.96         | 251.96       | 40.39  | 0.0001  |
| Error               | 12 |             | 74.85          | 6.24         | -      | -       |
| Total               | 19 |             | 3421.66        | -            | -      | -       |

![Fig. 5: Three-dimensional illustration of the effects of the engine’s load and speed on the smoke opacity rate in B50 fuel.](image-url)
2.4.3 Optimization of the smoke opacity rate for biodiesel percentage, and the engine’s speed and load

The lowest level of smoke generated by the engine (9.37; on the soot opacity scale) was observed under applying a 20\% load, the rotational speed of 1261 rpm, and when using pure biodiesel fuel. The highest level of smoke production (66.18; on the smoke opacity scale) was observed under an applied load of 89.58\%, the rotational speed of 1000 rpm and when using pure diesel fuel.

2.5 Minimizing pollution characteristics

According to the results, the lowest level of pollutants (CO, CO₂, HC, NOX) and smoke opacity occur under an applied load of 41.36\%, rotational speed of 1383 rpm and when using mixed fuel D_{12.4}B_{67.53} with 60\% utility. Generally, the least level of pollutant emission will occur at lower loads and speeds as well as high percentages of biodiesel. Under these optimal conditions, the CO and CO₂ emission rates are 0.043 and 0.63 (in vol\%), respectively, while the HC and NOX pollutant emission are of 51.34 and 191.98 ppm, respectively. The smoke opacity rate is 20.94\% (on the smoke opacity scale) (Fig. 7).

In a similar study by Wu et al.\(^{26}\), studying five different types of biodiesel found that HC emissions decreased by 45 to 67\%, which is similar to the results of the present study. When pure biodiesel was used instead of diesel, HC emission was reduced, the lowest HC emission was 33.52 ppm. But in Banapurmatha et al.’s (2008) study\(^{28}\), different results were obtained. They believed the HC emission from biodiesel was higher compared to diesel fuel. That is why low volatility of biodiesel was considered. Also in another research in a 2009 by Nabi et al., a maximum increase (15\%) of nitrogen oxide was observed for B100 under full load conditions, which is comparable to the results of this research optimizing the maximum NOX emissions for the B100. Pure biodiesel fuel and 2467 rpm speed and 94.24 percent engine load occurred with similar results\(^{36}\).

3 Results

The present study was aimed at investigating the possibility of using different diesel-biodiesel blends, the effect of engine’s load and speed, as well as different volume ratios of diesel and biodiesel blends on the pollution characteristics. The findings include:

- Increasing the content of biodiesel in the blended fuel...
will lead to a decrease in the HC emission rate. The lowest 
HC emission rate (33.52 ppm) was observed when using the 
B62.6 fuel blending, at a rotational speed of 1837 rpm and 
under the load level of 95%.

As the load increased, the NOx emission rate is increased 
for all fuel blends. The NOx emission rate will be increased, 
following an increase in the content of biodiesel in the 
blended fuel. The lowest NOx emission rate (145.08 ppm) 
was observed when using 8% biodiesel fuel under the load 
level of 20% and a rotational speed of 1560 rpm.

With increasing the biodiesel content in the blended fuel, 
the smoke opacity rate is reduced, so that the lowest level 
of smoke production by the engine (0.9% at smoke opacity 
-scale) was observed under the load level of 20%, the rota-
tional speed of 1261 rpm, and when using pure biodiesel.

The lowest HC and NOx and smoke opacity rate were 
observed under the load level of 41.36%, the rotational speed 
of 1383 rpm, and when the use of D52,B67.6 blended fuel 
with the utility of 60%.

The lowest emission rates of all pollutants were observed 
under average engine load and speed and high percentages 
of biodiesel.

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