

RESEARCH ARTICLE

Analysis of Performance of Engine and Exhaust Emissions with Modified Biodiesel Fuel

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Abstract

Biodiesel fuel is used in internal combustion diesel engines because it is superior to other fuels. Biodiesel is renewable and non-petroleum based, with lower carbon monoxide, hydrocarbon, and particulate matter emissions. The current work aimed to explore the use of modified biodiesels in a single-cylinder direct-injection diesel engine at partial load condition. Influences of the compound structure of neat and modified biodiesels components on engine performance and exhaust emissions were compared with diesel fuel. Modified biodiesels for testing were prepared by adding methyl oleate (MO) to palm oil methyl ester (PME) at specified volumetric ratios: PME80:MO20, PME70:MO30, PME60:MO40, and PME50:MO50 (vol/vol%). Furthermore, the effect of key fuel properties of PME and modified biodiesels on engine performance and exhaust emissions was discussed. Experimental results showed that modified biodiesels generated a lower brake torque with higher brake specific fuel consumption (BSFC) compared with that of petroleum diesel because of the former's calorific value and higher kinematic viscosity.

Essential reductions in carbon monoxide (CO) and hydrocarbon (HC) emissions were observed for these modified biodiesels; with a slight increase in nitrogen oxide (NOx) emission. Moreover, tested modified biodiesels improved in terms of brake torque and BSFC and showed slightly increased CO, HC, and NOx emissions over their parent PME as a result of the lower ignition quality and lower oxygen content of modified blends. Consequently, biodiesel possesses more saturated components and higher oxygen content and produced lower CO, HC, and NOx emissions. Consequently, BSFC increased.

Keywords: Modified Biodiesel; Engine Performance; Engine Emissions

Introduction

Biodiesel fuel is a mixture of mono-alkyl esters of vegetable oils or animal fats. Methyl esters can be yielded by transesterifying the parent oil or fat to achieve viscosity and flow properties similar to those of diesel fuel. The fatty acid profile of biodiesel depends on the parent oil or fat. The most common fatty esters contained in biodiesel are derived from palmitic, stearic, oleic, and linoleic acids [1]. Palm oil is derived from a perennial plant that grows in tropical regions, especially in humid lowlands. Palm oil generally has the highest oil yield among other common biodiesel raw materials; its oil production is about 13 times higher than that of soybean. Previous studies have shown that biodiesel production cost mainly depends on feedstock cost, which constitutes about 75%–80% of the total production cost. Therefore, the choice of biodiesel feedstock with a high oil yield is a crucial for low-cost biodiesel production [2]. However, the major problem associated with palm oil biodiesel is its poor low temperature property [3].

Different methods have been suggested to improve the cold-flow properties of biodiesel. Among the most commonly utilized are the following: (i) blending with petroleum diesel fuel [4-6], (ii) transesterification with branched chain alcohol [7,8], (iii) additives utilization of [9-12], (iv) winterization to decrease the level of saturated fatty acids in the feedstock [13], and (v) blending of biodiesels from different sources [14-16]. Methyl esters from highly saturated feedstocks are usually blended with other methyl esters with better cold-flow properties to obtain a satisfactory performance at low temperature. Furthermore, using more saturated FAMES with cheaper FAMES in the blend reportedly decreases raw material costs [17]. Methyl oleate was recently proven to improve effective cold-flow when added to palm oil methyl ester. Methyl oleate concentrations of up to 50% (vol%,vol%) could improve cloud point and cold filter plugging point of palm oil methyl ester by approximately 70.38%, and 91.69%, respectively. Other properties of this modified biodiesel have been observed within specified permissible limits of biodiesel standard (ASTM D 6751) [18].

However, several studies analyzed the effect of the structural components of the fatty acid alkyl esters, particularly unsaturation degree and chain length, on engine performance and exhaust emissions. A strong correlation between the unsaturation degree and properties of biodiesel was observed. Moreover, increasing the level of unsaturation degree for feedstock decreased cetane number, kinematic viscosity, and oxidation stability, and simultaneously increased lubricity, iodine value, and density [19]. Using biodiesel fuels in diesel engines can reduce CO, HC, and PM emissions because of the higher oxygen content of biodiesel compared with that of diesel petroleum [20]. However, previous papers reported that NO_x emissions increased when biodiesel fuel is used in a diesel engine. Furthermore, NO_x emission formation as a result of burning biodiesel fuel strongly depends on the unsaturation degree and cetane number of biodiesel [21]. The effect of unsaturation degree on the emission characteristics has been previously studied [22].

Three different biodiesels were suggested, namely, palm oil biodiesel, linseed oil biodiesel, and their blends were at 50% by volume. The degree of unsaturation of palm oil biodiesel was 50%, whereas this was approximately 10% for linseed oil biodiesel. Linseed oil biodiesel has significant polyunsaturated contents of approximately 70%. Results reported increased NO_x emissions, which is mainly influenced by the cetane number and unsaturation degree of biodiesel. Moreover, cetane number was inversely correlated with NO_x emissions [23]. Wyatt, *et al.* [24] reported that biodiesel has high saturation and can reduce NO_x emissions levels.

The objective of this work is to analyze the performance of engine and exhaust emissions with modified biodiesels which were suggested to be an effective cold-flow improver that enhanced cold flow properties of palm oil methyl ester [18]. Specifically, modified biodiesels in this work were prepared by adding MO to neat PME at the following specified volumetric proportions (vol/vol%): PME80:MO20, PME70:MO30, PME60:MO40, and PME50:MO50. Brake torque (BT), brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), CO emissions, HC emissions, and NO_x emissions for PME and tested modified biodiesels, were compared with those of diesel fuel. Effects of different properties of the tested fuels on engine performance and exhaust emissions were discussed.

Materials and Methods

Materials

MO (technical grade 70%) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Other chemical and reagents used were of analytical grade and acquired from Merck Chemicals, whereas the refined palm oil was obtained from a local refinery.

Biodiesel Production

Alkaline-catalyzed trans esterification yielded palm oil methyl ester using sodium hydroxide and methanol alcohol. Palm oil was mixed with methanol alcohol at a 6:1 molar ratio of methanol to oil and catalyst (NaOH) (1 w/w% of oil) in a jacket reactor at 60 °C. The mixture was stirred for 1 h at 600 rpm. The reacted material was poured into separation funnels for 12 h to complete the separation. The upper layer contained biodiesel (methyl ester), whereas the lower layer contained glycerol and other impurities. Pure biodiesel was washed using distilled water to remove the residual impurities and using glycerin to obtain purified biodiesel. Distilled water (50% v/v) was added to the produced ester, and the mixture was gently shaken at 50 °C-55 °C. The product was washed several times, and the pH became neutral. The biodiesel was then subjected to vacuum distillation using a rotary evaporator at 65 °C for 1 h to remove any residual methanol alcohol.

Preparing of Modified Biodiesel

In this work, the modified biodiesels of methyl esters were prepared by adding methyl oleate (MO) to palm oil methyl ester (PME) in the following specified volumetric proportions: PME80:MO20, PME70:MO30, PME60:MO40, and PME50:MO50 (vol/vol%). These modified biodiesels were described as follows: P80:O20, P70:O30, P60:O40, and P50:O50, respectively. Table 1 shows physiochemical properties of PME and modified biodiesels.

Properties	PME	P80:O20	P70:O30	P60:O40	P50:O50
Cold filter plugging point °C	16	12.33	8.67	5	1.33
Oxidation stability h	12.5	10.69	8.66	6.27	4.14
Cetane number	69.63	67.78	66.99	65.79	64.67
Kinematic viscosity mm ² /s	4.89	4.86	4.82	4.78	4.76
Net heating value MJ/kg	35.41	35.53	35.97	36.28	36.62
Acid value mgKOH/g	0.19	0.26	0.34	0.42	0.47
Oxygen content (wt.%)	11.25	11.24	11.22	11.19	11.16
Saturated methyl esters	44.25	39.05	36.5	32.92	28.96
Unsaturation degree (wt.%)	55.75	60.95	63.5	67.08	71.04

Data obtained from ref [18]

Table 1: Major physico-chemical properties of PME and modified biodiesels

Test of Engine

Apparatus of Test

Engine power was experimentally tested in a naturally aspirated single-cylinder diesel engine brand Yanmar model L48N. The engine test bed is shown in Figure 1. Various fuels were investigated in this experiment, as follows: diesel, PME, P80:O20, P70:O30, P60:O40, and P50:O50. Table 2 shows the engine specifications. This engine was coupled with the Xiang Yi eddy current dynamometer (Table 3) and ANYCAR- AUTOCHEK gas analyzer (Table 4) to measure exhaust gas emission at certain speeds. The engine included a fuel tank with a fuel supply valve, weighing balance, exhaust hose, thermocouple exhaust temperature sensor, air velocity sensor, inlet air temperature sensor, pressure sensor for monitoring fuel pressure in the fuel tank, and dynamometer control panel with indicators to display results. The engine was not a governor-controlled engine and had no combustion analyzer. The test bed measured torque, speed, fuel consumption, air flow rate, inlet temperatures, engine oil cooling water, and exhaust gas temperature; other engine performance parameters were also calculated.



Figure 1: The engine test bed

Particulars	Details
Brand	Yanmar engines
Model	L48N
Combustion system	Direct injection
Type	1-cylinder, 4-cycle diesel engine
Aspiration	Natural aspiration
Cylinder bore × stroke	70 mm × 57 mm
Displacement	219 cc
Maximum power output	3.1 Kw/ 3000 rpm
Continuous power output	2.8 kW/ 3000 rpm
Cooling system	Air cooled
Starting system	Recoil starter

Table 2: Engine specifications

Particulars	Details
Manufacturer	Xiang Yi
Model	GW 10
Rated absorbing power	10 Kw
Rated braking torque	50 Nm
Rated maximum speed	13,000 rpm
Coolant	Fresh water
Measuring accuracy of torque	± 0.2-0.3 %
Measuring accuracy of rotational speed	± 1 r/m

Table 3: Specifications of dynamometer

Component	Measurement	Measurement range	Resolution
CO	Non-dispersive infrared (NDIR)	0-10 vol.%	0.03 vol.%
CO ₂	NDIR	0-20 vol.%	0.03 vol.%
HC	NDIR	10,000 ppm vol.	1 ppm
Nox/NO	Electrochemical	5000 ppm vol.	1 ppm

Table 4: Exhaust gas analyzer specification

Furthermore, to ensure accuracy of torque measurements, dynamometer calibration was conducted prior to the test. The calibration device included calibration arm tray and a set of counter weights. The eddy current dynamometer control device was connected to the control cables. After attaching the calibration arm tray to the dynamometer, the zero point was set before adding any counter weight to calibration arm tray. The full-scale of the instrument was then established after adding a full scale of counter weights to the calibration arm. The zero point was checked after removing all counter weights from the tray. To check and compare the torque display value with the counter weight value, the counter weight was added to the tray and gradually increased to full scale. Finally, weight was gradually reduced to zero; the torque display value was compared with the actual weight.

Engine Test Procedure

To determine the engine performance at a partial load condition, the engine was run and allowed to warm up for several minutes at half throttle, then the throttle was gradually increased to approximately 3000 rpm with no load. Load was then gradually increased to the specified load (50%) of the observed full load to obtain parameters at different speeds. Engine performance data was collected after the engine completely reached steady-state operation conditions. The steady-state operation conditions were determined by monitoring changes in the engine exhaust temperature, which was displayed on a meter fixed on dynamometer control unit. When the change (difference) in exhaust temperature was less than 1%, the engine was at steady state. Monitoring required 2 min to reach the steady state of engine. Once measurements were stabilized, data collection began. Upon completing data collection at this speed, the load on the engine increased until the engine speed decreased to the next desired engine speed. Measurements were allowed to re-stabilize, and data collection was repeated. Testing was done repetitively for each desired engine speed. Engine speed and torque were used to determine the horsepower of the engine at each targeted speed. The speeds those were sufficiently stable for testing were 3000, 2800, 2600, 2400, 2200, 2000, and 1800 rpm.

Exhaust Emission Procedure

A newly calibrated gas analyzer (ANYCAR-AUTOCHEK) was used to measure exhaust gas emission for various fuels at each desired speed under 50% load conditions. Exhaust concentrations for hydrocarbon (HC) emissions and nitrogen oxide (NO_x) emission were directly recorded in units of one part per million (ppm) from the gas analyzer, whereas carbon monoxide (CO) emission concentration was recorded in percentage (%) and converted to ppm by multiplying the CO concentration (%) by 104. Furthermore, the measurements of HC, NO_x, and CO emissions were simultaneously conducted with fuel performance tests. Three measurements for each pollutant were averaged to represent the pollutant exhaust concentration.

After parts of gas analyzer were collected and powered, it was allowed to warm up for 10 min. The gas analyzer probe was then attached to the exhaust engine system outlet. Each fuel was tested at engine loading value (corresponding to approximately 50% of the engine) with different specified speeds. For each test, emission data were collected after the collection of engine performance data when the engine was completely under steady-state operation conditions. Emission data was collected for 2 min. Testing for each engine speed was repeated thrice simultaneously with tests of performance.

The parameters brake power (BP), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE) were determined based on Equations. (1) to (3).

$$(BP, kW) = \frac{2\pi NBT}{60,000} \quad (\text{Equation 1})$$

$$(BSFC, g / kWh) = \frac{m}{BP} \quad (\text{Equation 2})$$

$$(BTE, \%) = \frac{3600}{LHV \cdot BSFC} \times 100 \quad (\text{Equation 3})$$

Where N is the speed of engine (rpm), BT is brake torque (Nm), m is fuel consumption (g/h), and LHV is net heating value MJ/kg.

Results and Discussion

Brake Torque

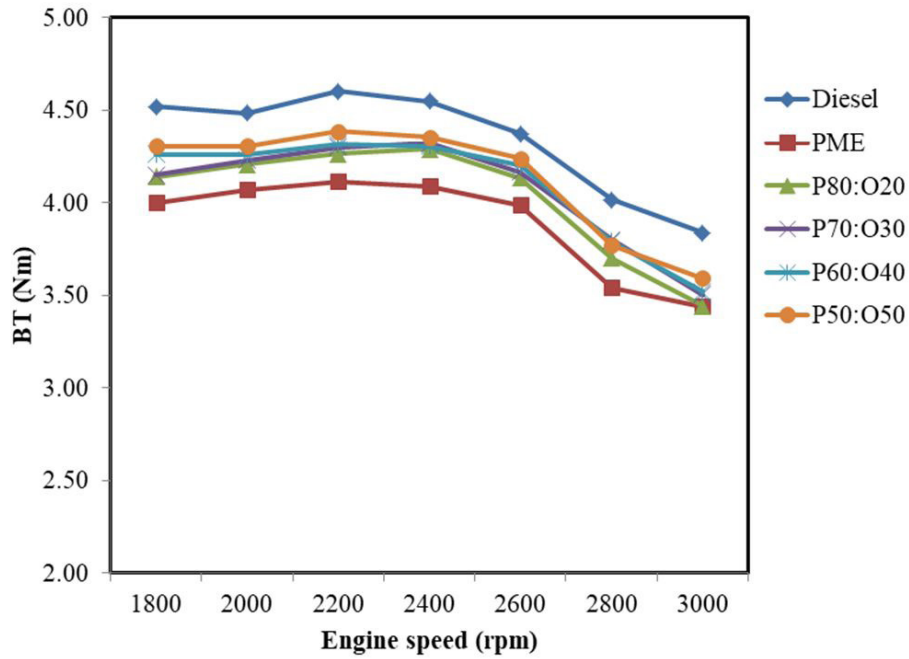


Figure 2: Variation of brake torque (BT) with respect to engine speed

Figure 7 shows the comparison of shell side heat transfer among the periodic model within the range of mass flow rate tested. The result shows that the heat transfer rate increases with increase in mass flow rate and pitch of the spiral baffle. The variation trend can be understood from two aspects. First, at fixed shell inner diameter and helix pitch and also cross flow area decrease with diameter with decrease in helix pitch. Second decrease in helical angle of spiral baffle.

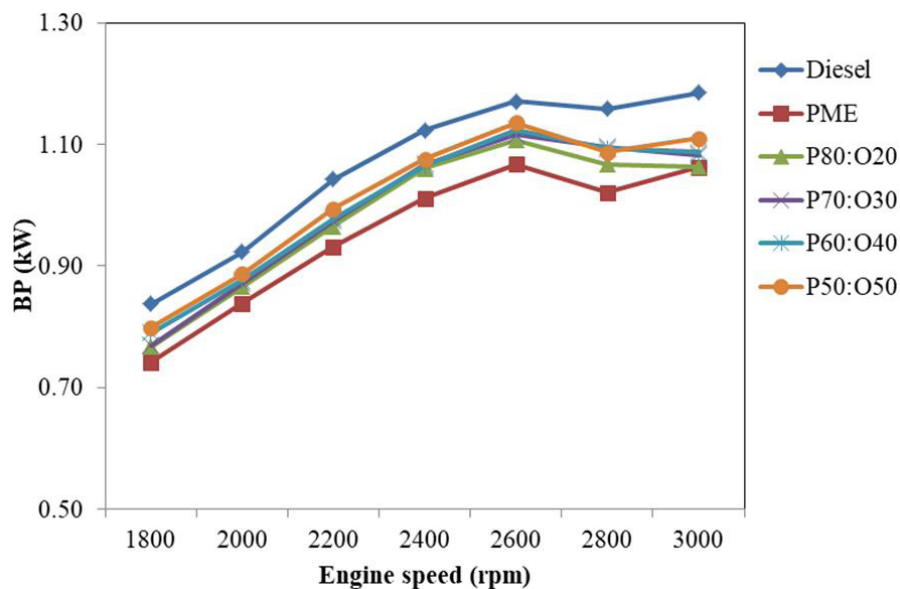


Figure 3: Variation of brake power (BP) with respect to engine speed

Brake Power

Engine brake power variations with respect to engine speed for diesel, PME, and modified biodiesels are described in Fig. 3. BP increased steadily with engine speed. Lower BP output of biodiesels was observed due to lower calorific values, and higher viscosities can be attributed a less efficient combustion than that of diesel fuel [28]. Among the PME and modified biodiesels, no major changes in BP output were observed.

Brake Specific Fuel Consumption (BSFC)

BSFC is fuel flow rate per unit power output and can be a measure of engine efficiency when using the supplied fuel to produce work. BSFC is the most important parameter for evaluating engine performance using different fuels. The BSFC of a diesel engine depends on the relationship between volumetric fuel injection system, viscosity, net heating value, and density [29]. BSFC of all fuels was compared in terms of engine speed are presented in Fig. 4. Moreover, the mean BSFCs for tested fuels over the entire speed range were 339.84, 414.13, 408.59, 410.07, 411.60 and 411.33 g/kWh, respectively. Minimum BSFC is kept for diesel fuel. Overall the reduction BSFC for PME and modified biodiesels increased by 21.86%, 20.23%, 20.66%, 21.11% and 21.04%, respectively, compared with diesel fuel. Increased BSFCs of all tested biodiesels can be attributed to their lower calorific values and oxygenated nature [30,31]. A slight improvement in BSFC for all tested biodiesels was also observed because of the combined effect of improved viscosity and net heating value. Accordingly, the BSFC of PME increased, thereby compensating for the reduction of chemical energy in the fuel and maintaining the same brake power output (Figure 4).

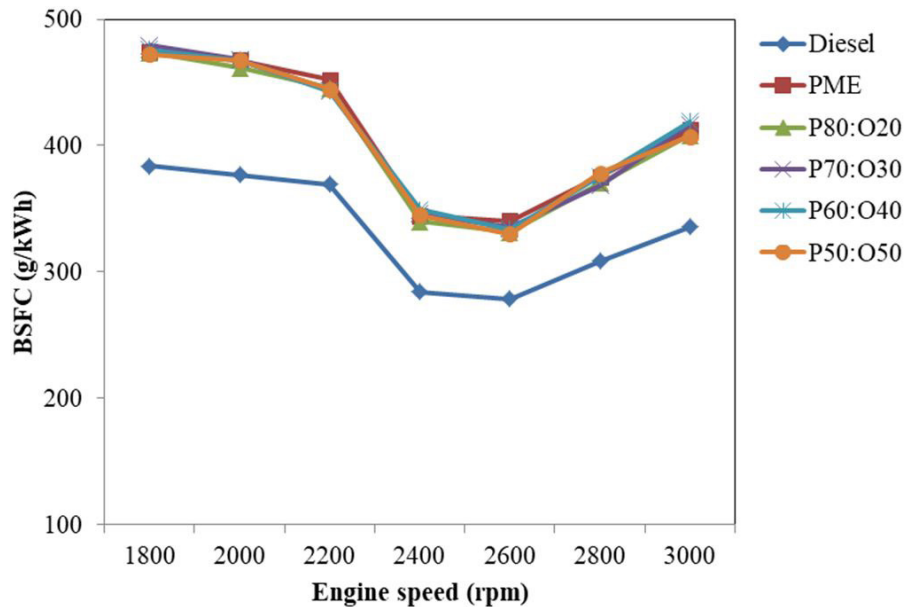


Figure 4: Variation of brake specific fuel consumption (BSFC) with respect to engine speed

Brake Thermal Efficiency (BTE)

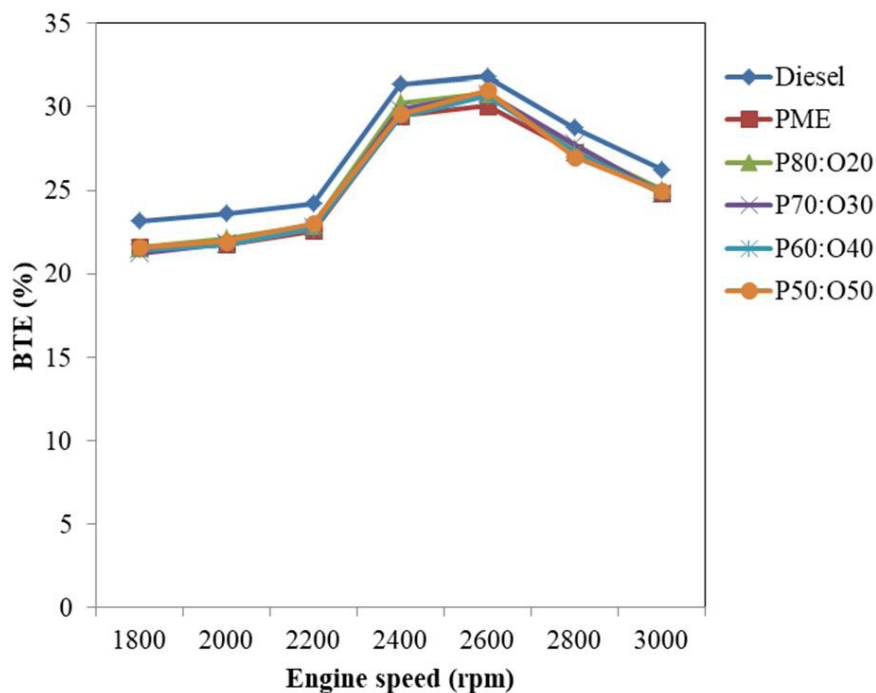


Figure 5: Variation of brake thermal efficiency (BTE) with respect to engine speed

BTEs for diesel and tested biodiesels with respect to engine speed are shown in Figure 5. The BTE of diesel engine is the efficiency at which the chemical energy of a fuel is turned into useful work; BTE has an inverse relationship with BSFC and the lower heating value of a fuel. BTE increases with increasing load for all tested fuels. However, BTE of PME and modified biodiesels are lower compared to that diesel. This reduced BTE of biodiesel is mainly caused by higher BSFC in spite of the lower calorific value of biodiesels [32]. BTE increased with increasing engine speed and then decreased slightly at 2800 and 3000 rpm because of the lack of spray characteristics of tested fuel and air–fuel mixing at high engine speed [33]. The mean BTEs for all tested fuels over the entire engine speed range were calculated to be 26.50%, 25%, 25.37%, 25.32%, 52.20%, and 25.22%, respectively. Overall reductions in BTE for PME and modified biodiesels were 5.66%, 4.26%, 4.45%, 4.90% and 4.830%, respectively, compared with that of diesel fuel. The decreased BTE for biodiesels can be caused by higher density and viscosity, as well as a lower calorific value than diesel, which can be considered major factors influencing the reduced BTE of tested biodiesels. The modified biodiesels led a slight improvement in BTE when compared with PME because of decreased kinematic viscosity, which enhanced atomization and fuel vaporization.

CO Emission

CO emissions for diesel and biodiesels with respect to engine speed are shown in Figure 6. CO is generally formed due to insufficient burning and partial oxidation of carbon atoms in a fuel. Particularly, CO emissions can be affected by engine speed, fuel type, and air–fuel ratio. High engine speed is known to reduce CO emission because of better air–fuel mixing process and increased fuel/air equivalence ratio [34,35]. Significant CO emission of PME and modified biodiesels was lower than diesel fuel and were calculated to be 78.30%, 76.24%, 74.50%, 71.45%, and 67.90%, respectively. This reduction is achieved mainly because of the oxygen content of biodiesel improving oxidation reactions and more fuel being contributed to combustion. Having sufficient oxygen in tested biodiesels causes CO₂ emissions through the oxidation of carbon monoxide.

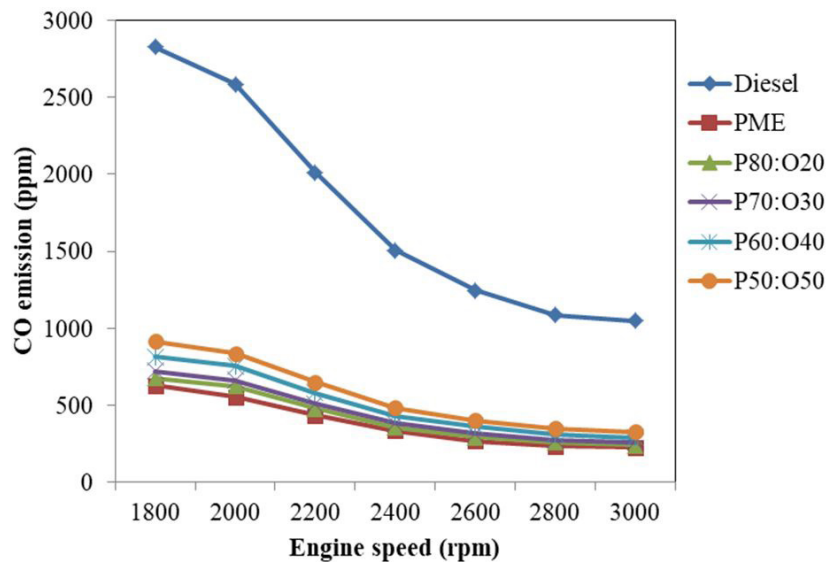


Figure 6: Variation of CO emission with respect to engine speed

Moreover, CO emissions increase with increased engine load. As the engine load increases, the oxygen concentration in the combustion chamber decreases. Hence, oxidation slows down. Insufficient turbulence in combustion chamber prevented the homogenous air/fuel mixture and caused CO formation [36]. Furthermore, CO emissions were slightly higher for all modified biodiesels higher than for PME because of oxygen content reduction by mass friction (Table 1), which promotes incomplete combustion [37]. As reported previously, CO emissions were significantly increased with decreasing saturated chain length level of biodiesels [38]. Thus, CO emission can be increased by reducing the saturated component amount of modified biodiesels (Table 1).

HC Emission

Incomplete combustion of fuel leads to unburned HC emission. The variation of HC emissions for diesel and tested biodiesels over a speed range of 1800–3000 rpm in Figure 7. HC emission increased with increased range of engine speed. Moreover, for all tested fuels, HC emission deteriorated with increased speed because of the higher injected fuel quantity, which decreased the air–fuel equivalence ratio [39]. The overall reduction in HC for PME and modified biodiesels were 68.40%, 65.73%, 63.30%, 58.40%, and 52%, respectively, which are lower compared with those of diesel. This variation is mainly because biodiesel has a 10% higher oxygen content, which facilitates a more complete combustion [40]. In addition, decreased HC emission was reportedly caused by the higher cetane number of biodiesel compared with that of diesel, which reduced burning delay [41]. However, HC emissions were relatively increased for the modified biodiesels because of the relatively low cetane numbers and oxygen content by mass friction (Table 1), which promoted incomplete combustion [42]. Moreover, increased HC emissions were found to be caused by reduced saturation levels of several biodiesels [43].

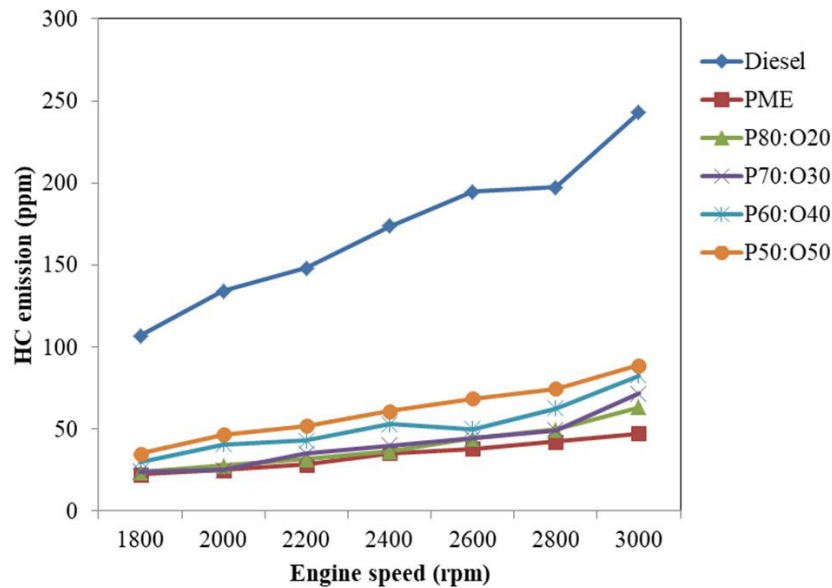


Figure 7: Variation of HC emission with respect to engine speed

NOx Emissions

NOx emission variations for diesel and tested biodiesels over a speed range of 1800–3000 rpm are presented in Figure 8. Particularly, NOx concentration increased in the exhaust was observed with increased engine speed. This behavior is due to increased gas flow motion within the cylinder under higher engine speeds, thereby leading to faster mixing of air and fuel and a shortened ignition delay. The reaction time of each engine cycle is reduced at high speed. Thus, the residence time of high gas temperature within the cylinder is short, thereby leading to lower NOx emissions under higher engine speed [44]. The overall increase in NOx emissions for PME and modified biodiesels were 5.60%, 6.70%, 10.10%, 12.10% and 14.40%, respectively, when compared with that of diesel fuel. This result agrees with those of many studies, which reported that biodiesel can result to higher NOx because of its relatively high oxygen (~12%); this high oxygen content leads to complete combustion and higher combustion temperature, which increased NOx emission [45-47].

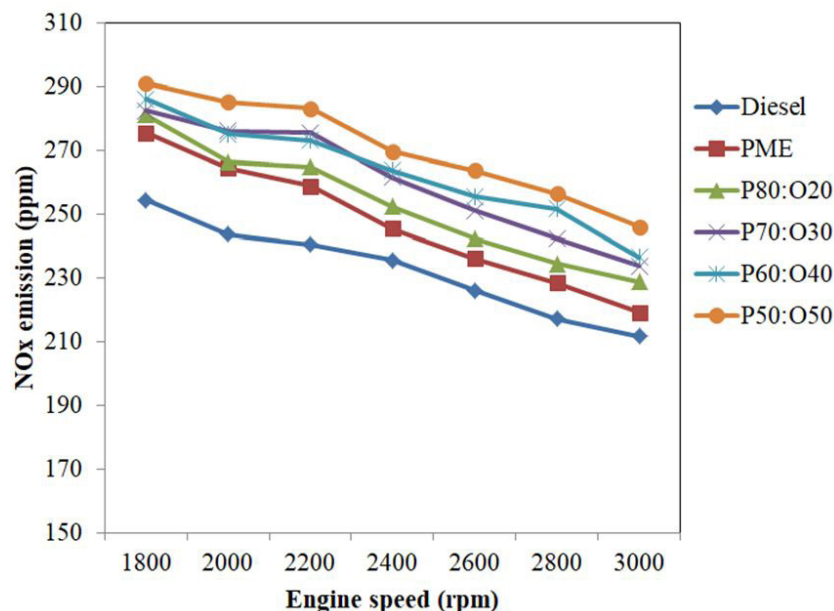


Figure 8: Variation of NOx emission with respect to engine speed

In addition, the higher viscosity of biodiesel can be attributed to the injection of a bigger droplet size and shorter ignition delay, thereby increasing NOx emission [48]. The higher NOx emission of the modified biodiesels compared with that of PME was due to the increasing unsaturated component quantities. Lower amounts of unsaturated components (Table 1) resulted in a shorter ignition delay and less premixed burning and, thus, lower combustion rates. Consequently, lower in-cylinder bulk-gas-averaged temperatures were achieved during combustion, which can inhibit thermal NOx emission [49].

Conclusion

Engine performance and exhaust emissions pure PME and its modified biodiesels with methyl oleate (MO) (technical grade) were investigated by subjecting a direct-injection single-cylinder diesel engine at partial load condition. The modified biodiesels were compared with diesel fuel. Modified biodiesels were prepared by mixing MO with pure PME at specified volumetric proportions, namely PME80:MO20, PME70:MO30, PME60:MO40, and PME50:MO50. Under 50% load condition, increased MO proportion to pure PME till 50, vol% slightly improved the generated brake torque. Moreover, increasing the MO proportion to pure PME until 50 vol% remarkably reduced BSFC with respect to that of PME, which can be attributed to improved calorific value and kinematic viscosity. The brake torque and BSFC were possibly influenced by the lower heating value and higher kinematic viscosity of PME and modified biodiesels compared with those of diesel fuel.

Accordingly, PME and modified biodiesels possessed useful properties in terms of CO and HC emissions. Reduced CO and HC emissions were maintained and were probably due to higher cetane number and oxygen content in biodiesels. By comparison, modified biodiesels yielded higher NO_x emissions than diesel fuel. However, modified biodiesels resulted in increased exhaust emissions that were slightly higher than PME.

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