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Improvement in cold flow properties of biodiesel and its effects on diesel engine performance and emissions

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Abstract
An experimental analysis was conducted to test the feasibility of biodiesel in the regions experiencing adverse cold weather conditions. Biodiesel was produced from canola oil by transesterification and fractionation processes. Winter diesel was used as a reference fuel. Three different fuel series were used: diesel-biodiesel with three blends (B20, B50 and B100), diesel-fractionated biodiesel (FB20, FB50 and FB100), and diesel-fractionated biodiesel with 2 volume percent of Wintron Synergy series (FB20S2, FB50S2 and FB100S2). All the fuel blend series were tested on a two-cylinder light-duty diesel engine to investigate effects of fuel blends on performance and emissions, under low, medium and high loads, at engine speeds of 1000, 2100 and 3000 rpm. Normal biodiesel and fractionated biodiesel with 2 vol% synergy showed significant improvement in the cloud point. FB40S2 had the lowest cloud point compared to other fuel blends measuring -48.5˚C. The emissions of carbon monoxide (CO), unburned hydrocarbon (HC), oxides of nitrogen (NOx) and smoke opacity from different fuel blends were measured and compared to that of diesel fuel. It was found that fractionated biodiesel and synergy blends were effective in reducing CO, HC and smoke emissions; however, all biodiesel blends increased NOx emission. Investigation results indicated that fractionated biodiesel with 2 vol% synergy had better engine performance and lower emission compared with diesel fuel and normal biodiesel blends. Thus, fractionated biodiesel up to 80 vol% with 2 vol% synergy was suitable for use in diesel engines in extreme winter conditions in Canada without the need for any engine modification.

Keywords: Biodiesel; Cold flow additive; Engine load; Diesel engine; Emissions.

1. Introduction

Biodiesel produced from plants and animals have been regarded as an important renewable energy as it can be used directly or blended with diesel fuel without any requirements in engine modifications. As compared with conventional diesel, biodiesel is advantageous with enhanced biodegradability, reduced toxicity, improved combustion efficiency and increased lubricity [1]. Canola oil has been used widely for the production of biodiesel as it contains the least saturated fat of any common edible oil in the market. Almost 93% of the fats in canola are monounsaturated and polyunsaturated fatty acids which could improve cold flow properties (CFP) of biodiesel. However, canola oil biodiesel cannot be used in extreme cold weather conditions like in Canada [2]. Therefore, improving the cold flow properties of canola biodiesel is important. The cloud point (CP) is the temperature at which fatty acid compounds become cloudy due to formation of crystals and solidification of saturates. Several methods have been proposed in literature to improve the cold flow properties of biodiesels: blending with diesel, adding additives, and winterization of biodiesel with fractionation process. The well accepted method to reduce the crystal accumulation with decrease in temperature could be blending biodiesel with additives, which not only improves the cold flow properties, but also improves the emissions [3]. Many studies have been done on winterization of biodiesel and its effect on cold flow properties of biodiesel [4], which have indicated that biodiesel produced from feedstocks usually require certain winterization processes to achieve some particular type of saturated fatty acid reductions, as the components of saturated fatty acid differs for a specific feedstock. Vegetable oils are mixtures of triglycerides from various fatty acids, and fatty acids with long carbon chains affect CFPs.

A study by Verma et al. [5] on the experimental analysis of palm biodiesel found that CP and pour point (PP) of palm biodiesel improved significantly by blending with diesel fuel, while blending with kerosene showed remarkable enhancement. Bhale et al. [6] studied the effect of ethanol, kerosene and additives on cold flow properties of biodiesel; it was concluded that biodiesel-ethanol blend was a sustainable alternative fuel to improve cold flow behavior and reduce CO, NOx and smoke emissions without affecting the engine performance. Studies in [7] showed that two branched chain fatty acid methyl esters (BC-FAME) mixed with biodiesel produced from canola, palm and soybean oil could decrease their CP and PP. It was found that increasing BC-FAME between 17 and 39 mass percentage helped improve the CP and PP of the biodiesel blends without increasing the viscosity under the specified limits of ASTM standards. Chastek [8] tested several solvent and polymeric additives to improve the CFP of canola biodiesel; and it was found that 1% of poly (lauryl methacrylate) improved the cold filter plugging point (CFPP) and PP by 20˚C and 30˚C, respectively.

To overcome the problem of lower yield in fractionation process with no significant reduction in PP, researchers have come up with an idea of winterizing methyl esters with different solvents, such as methanol, acetone, chloroform and hexane [9]. Methanol, which is easily available in the market, offers the benefit that winterization may be easily incorporated into the industrial biodiesel production facilities. The saturated methyl esters showed a higher immiscibility in methanol than the high molecular linear alcohols in study [10]. Methanol has also been used as a reagent in transesterification process which may boost the winterization of biodiesel in industrial biodiesel production facilities. For example, winterization of beef tallow biodiesel was done in [11] by fractional crystallization to reduce the saturated fatty acid content. The results showed reduction in CP from 21˚C to 17.4˚C, PP from 10.8˚C to 3.5˚C, density from 899 kg/m³ to 861 kg/m³ and kinematic viscosity from 5.5 mm²/s to 5.32 mm²/s. Wang et al. [12] conducted experiments on improving the CFP of biodiesel produced from waste cooking oil by two different processes namely surfactants and detergent fractionation. From the surfactant tests, the highest reduction in CFPP was achieved from -10˚C to -16˚C by addition of 0.02 wt% polyglycerol ester. In addition, detergent fractionation showed lowest CFPP of -17˚C from waste cooking oil biodiesel with a yield of 73%. Supercritical CO_2 extraction and fractionation were tested in [13] to recover the jatropha curcas oil from biodiesel production. The highest amount of free fatty acids (26.3 wt.%) were extracted in the first fraction and then the pressure was increased to achieve higher amount of oil removal with very low amount of free fatty acids in the later stages.

The performance of engine using biodiesel is dependent on many factors such as fuel injection and fuel properties like oxygen content, lower energy content and higher viscosity of biodiesel. Verma et al. [14] found that brake specific fuel consumption (BSFC) of biodiesel produced from cotton seed oil decreased as the load on the engine increased. It was also found that as the percentage of biodiesel in blend increased, BSFC also tended to increase. The authors of this work also investigated the effect of canola biodiesel on a two cylinder, four stroke DI diesel engine under different load conditions in [15]. It was found that there was no significant effect on BSFC up to 10% of biodiesel blends. The BSFC of pure biodiesel increased to about 5% at low load condition and 9% at high load levels. The study concluded that biodiesel has higher fuel conversion efficiency than that of diesel fuel. Similar study in [16] also revealed that there was no effect of BSFC up to 5% blend of biodiesel or canola oil in diesel fuel but it generated 1.1% to 2.3% increase in BSFC on use of 20% blends at different speeds. A study in [17] using jatropha biodiesel blends on engine performance showed BSFCs for B10 was 4% lower than diesel fuel and B20 showed similar to diesel. However, B30, B40 and B50 generated 3.4%, 5.7% and 7.5% higher than diesel fuel. Ozener et al. [18] studied the characteristic of conventional diesel fuel and biodiesel produced from soybean oil and its blends. Compared to diesel fuel, the average brake torque decreased with increasing biodiesel concentration over the entire speed range under full load condition; it was concluded that the average BSFC values at all engine speeds for B100, B50, B20 and B10 blends were 9%, 7 %, 4% and 2% higher, respectively than those compared to diesel fuel. On the other hand,, Liaquat et al. [19] employed biodiesel-diesel blend (B20) produced from palm oil on a single cylinder, four stroke diesel engine during an endurance test carried out for 250 h at 2000 rpm and 10 Nm load. The test results indicated that the B20 blend had higher BSFC compared to diesel fuel. The average percentage increase in BSFC was 3.88% during endurance testing for B20 compared with diesel fuel.

In general, pure biodiesel and biodiesel blends could reduce particulate matters (PM), partially burned or unburned HC, CO_2, aromatics, poly aromatic hydrocarbons (PAHs) and CO emissions. However, there is usually a slight increase in NOx emissions compared to diesel fuels [20]. Armas et al. [21] tested biodiesel on a 4 cylinder, 4-stroke, turbocharged, intercooled diesel engine. The oxygenated biofuel was extracted from animal fats; the results showed lower HC, CO and PM emissions, and a slight decrease in NOx emissions using biodiesel. An et al. [22] studied the effects of emission from diesel engine with biodiesel produced from waste cooking oils under multiple idling conditions at 800 and 1200 rpm. The tests revealed that higher HC and NOx emissions were emitted at idle conditions but not at high rpm conditions, stating that low engine speed had significant effect on emissions when using biodiesel. Cheik et al. [23] conducted experiments using biodiesel blends on a naturally aspirated, direct injection diesel engine under different loads at 2500 rpm. The results demonstrated that the variation of engine speed and load had a great influence on engine emissions. Increasing the engine speed increased in HC emissions, however, increasing engine load generated higher emissions of CO and PM. Due to higher amount of oxygen content in biodiesel blends, NOx emissions increased slightly. Yanh et al. [24] conducted tests on a Euro IV diesel engine with biodiesel produced from waste cooking oil and its blends at four different engine speeds and under three different loads. The study revealed that low engine speed had a significant effect on the formation of CO, HC and NOx emissions. Zhang et al. [25] investigated the particulate emission characteristics of a single cylinder, direct injection diesel engine fueled with blends of butanol and pentanol in biodiesel at 10% and 20% by volume. The engine was operated at a constant engine speed of 3000 rpm and at three engine load of 25%, 50% and 75%. It was found that organic carbon and water soluble organic carbon decreased significantly with loads whereas elemental carbon increased with loads. Both the alcohol blends were able to effectively reduce particulate mass, elemental carbon emissions and PAHs at different load levels. A study done by Lanjekar et al. [26] found that coconut and palm kernel oils having high content of lauric acid produce lower amount of NOx emissions, better oxidative stability and CFP. Paper [27] investigated the performance and emissions of a four stoke, turbocharged, direct injection, four cylinder, and high-pressure common rail diesel engine with coconut biodiesel (B10, B20, B30 and B50) under different loading conditions. It was found that the BSFC was higher at different load conditions due to lower calorific value of biodiesel. CO emissions decreased and NOx emissions increased with increase in biodiesel concentration in the blend and engine load. At all load conditions, smoke emissions were lower with coconut biodiesel blends as compared with conventional diesel fuel.

As discussed in the aforementioned literature review, although there have been a number of studies on performance and emissions of biodiesel fuel, however the main problem limiting the application of biodiesel is related to its poor low temperature properties, which have not been studied adequately. There are limited studies on fractionated biodiesel being treated as a blending fuel for improving low temperature properties of biodiesel for cold climatic conditions. The objective of this study is to improve the CFP of biodiesel especially in adverse cold weather conditions. In this study, biodiesel will be blended with a reference fuel (i.e. winter-diesel). Urea fractionation will be treated with pure biodiesel to improve its cold flow properties. Fractionated (winterized) biodiesel and its blend with winter diesel will be blended to compare its CP with winter diesel. Wintron Synergy will be selected as the cold flow improver, which is a combination of polymethacrylate (PMA) compounds in a solution of mineral oil [28]. 2 vol% of Wintron Synergy will be blended with fractionated biodiesel-winter diesel blends to enhance the CFPs of fractionated biodiesel fuel series. This study also compares performance and emissions of different biodiesel blend (normal biodiesel, fractionated biodiesel and fractionated biodiesel with additive) to that of diesel fuel.

2. Methods and materials

2.1 Biodiesel production process

In this study, canola oil will be used for the production of biodiesel. Transesterification has been widely accepted as the simplest way for the production of biodiesel. The transesterification of vegetable oils with methanol and sodium hydroxide catalyst produces biodiesel and glycerine as a by-product. One litre of canola oil can produce approximately the same amount of biodiesel. Glycerol was separated from biodiesel, and then biodiesel was washed twice. The volumetric collection efficiency, after washing, averaged a total amount of 80%. Canola oil was purchased from the local supermarket. The biodiesel production quality was tested according to ASTM 6751, which can be found in Table 1.

Table 1. Properties of canola biodiesel.

Test Name	Test Method	ASTM limit	Results
Free Glycerin (mass%)	ASTM D6584	Max. 0.02	0
Total Glycerin (mass%)	ASTM D6584	Max. 0.24	0.112
Flash Point, Closed Cup (^{0}C)	ASTM D93	Min. 130	169
Water & Sediment (vol.%)	ASTM D2709	Max. 0.050	0
TAN (mg KOH/g)	ASTM D664	Max. 0.5	0.14
Simulated Distillation, 50% recovery (^{0}C)	ASTM D2887	N/A	359.8
Cetane Index	ASTM D976 (2 variables formula)	N/A	50
Copper Corrosion, 3h @ 50^{0}C (rating)	ASTM D130	Max. 3a	1a

2.2 Urea fractionation

This method is used to fractionate biodiesel into its saturated and unsaturated components. Urea has been proved to form an adduct with saturated biodiesel. Urea in the presence of suitable amount of guest molecule would form hexagonal channels that allow for guest addition. Crystalline solids would precipitate out of the urea-methanol-biodiesel mixture (usually containing the urea-saturated biodiesel adducts) when the solution is kept for a day at room temperature. A portion that is high in unsaturated fatty acid esters would have a much lower CP than the portion high in saturates [29]. The production of fractionated biodiesel is illustrated in Figure 1.

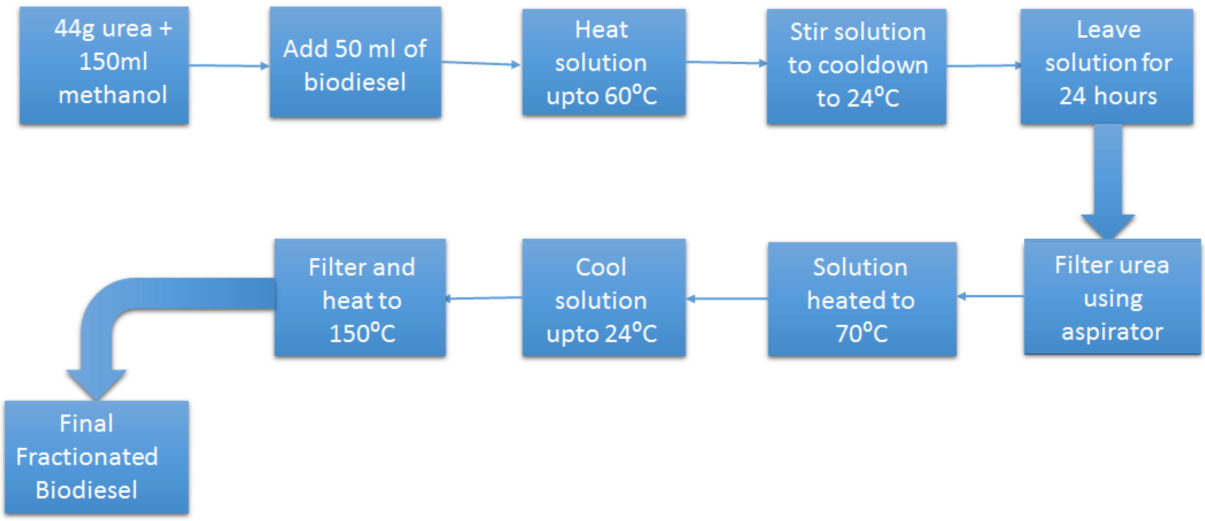


Figure1. Method of fractionation process.

All the tests except CP were performed at Lakehead University. Fuel samples were sent to a Canadian laboratory to determine CP. Table 2 summarises the density, viscosity, heating value and CP of the tested fuel blends. CP decrease is highest with fractionated biodiesel + 2 vol% Wintron Synergy. The CP of B20 (-28˚C) is decreased to -36.6˚C for FB20 and to -47.5˚C for FB20S2, which is about 9˚C and 19˚C reduction, respectively. Similarly from B50 to FB50 and FB50S2, the CP reduction is 19˚C and 32˚C, respectively, and from pure biodiesel (B100) to fractionated biodiesel (FB100) and with 2 vol% synergy (FB100S2), the CP reduction is 27˚C and 33˚C respectively. The highest viscosity was measured with FB100S2 (5.19 cSt) which is lower than the ASTM maximum limit of 6 cSt.

Table 2. Fuel properties of biodiesel, biodiesel-diesel, fractionated biodiesel-diesel, fractionated biodiesel-synergy blends.

Fuels	Cloud Point (^{0}C)	Heating Value (kJ/Kg)	Density (kg/m³)	Viscosity (cSt @ 40^{0}C)
B20	-28	44519	840	2.46
FB20	-36.6	44486	843	2.45
FB20S2	-47.5	43887	850	2.67
B50	-16	42953	855	3.22
FB50	-35.6	42855	863	3.29
FB50S2	-48.2	42265	870	3.51
B100	-2.6	40296	880	4.33
FB100	-31.7	40136	895	4.41
FB100S2	-37.7	39564	901	5.19

2.3 Engine under study

A light-duty diesel engine has been used in this study at variable engine loads and speeds, which is a Hatz 2G 40 with air-cooled 2-cylinder four stroke DI diesel engine. Figure 2 shows the schematic diagram of the experimental test setup for the light-duty engine. Table 3 summarizes the engine specifications.

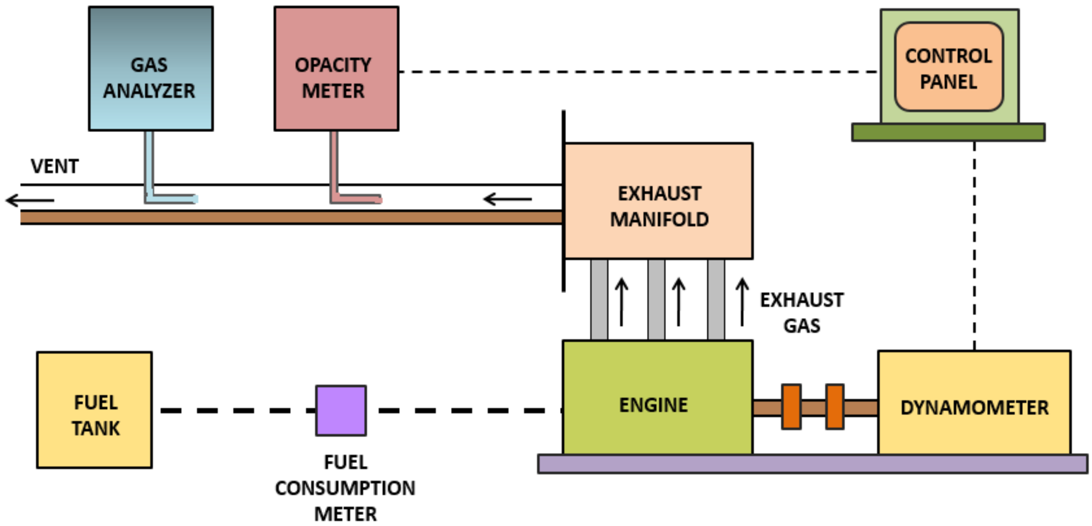


Figure 2. Schematic diagram of diesel engine test setup.

Table 3. Engine specifications of light-duty engine.

Engine Make and Model	Hatz 2G40/2G40H
Engine Type	Four stroke
Number of Cylinders	Two
Bore/Stroke	92mm/75mm
Displacement	997 cm³
Compression Ratio	20.5:1
Max. rated power	17 kW @ 3600 rpm

2.4 Engine test procedure

The tests were conducted to examine the performance and emissions of various winter diesel fuel blends on the engine. The first series consisted of winter diesel blends which have been blended with normal biodiesel at different volume percentages (20 vol%, 50 vol% and 100 vol%). The second series comprised of fractionated biodiesel blends in which winter diesel was blended with fractionated biodiesel at three different volume percentages (20 vol%, 50 vol% and 100 vol%). Finally, winter diesel-fractionated biodiesel was treated with 2 vol% Wintron Synergy with 20 vol%, 50 vol% and 100 vol% of fractionated biodiesel.

The engine was tested over 90 minutes under low, medium and high loads at different engine speeds for each fuel blend. At the beginning of each test, engine was run for warm-up for approximately 10 minutes. CO, HC, NOx and smoke emissions were measured at each engine load and speed at an interval of one minute. A multi-gas analyzer (NOVA Model 7466 PK) was used to measure regulated emissions. A separate CO analyzer (DWYER 1205A) with better resolution was used to measure the CO emissions. A smoke opacity meter was used to measure the smoke opacity. Specifications on measurement devices are summarized in Table 4. At least three tests of the same condition were performed and the average value is used to plot a graph. Similar conditions are maintained for all the tests for better comparison of the results .

Table 4. Gas analyzer specifications.

Method of Detection	Species	Measured Unit	Range	Resolution	Accuracy
NovaGas 7466K					
ElectroChemical/ Infrared detector	CO	%	0-10%	0.10%	±1%
Infrared Detector	CO_2	%	0-20%	0.10%	±1%
Electro Chemical	NO	ppm	0-2000 ppm	1 ppm	±2%
Electro Chemical	NO_2	ppm	0-800 ppm	1 ppm	±2%
Electro Chemical	O_2	%	0-25%	0.10%	±1%
Infrared Detector	HC	ppm x 10	0-20000 ppm	10 ppm	±1%
Dwyer 1205A					
Electro Chemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10	Temp	0.1 ^{0}C	(-)200^{0}C to 1360^{0}C	0.1^{0}C	±0.3%
Smart 2000	Opacity	%	0-100%	0.1%	±5%
	Soot Density	mg/m³	0-10 mg/m³	0.00001	±5%

3. Results and discussion

3.1 Cloud point

Figure 3 shows the variation of biodiesel content in diesel fuel and corresponding CP's. Winter diesel has a CP of -41˚C and that of pure biodiesel (B100) of -2.6˚C. It can be seen from Figure 3 that with addition of higher percentage of biodiesel in diesel fuel, CP becomes higher. Fractionation of biodiesel proved as an effective method for improving the CP of biodiesel. The lowest CP attained by fractionated biodiesel series is -36˚C with FB10. 100% fractionated biodiesel (FB100) has a CP of -31.7˚C. With 2% addition of cold flow improver, Wintron Synergy lowered the CP even more. FB10S2 and FB100S2 measured CP of -47.5˚C and -37.7˚C respectively. The lowest CP achieved among all the fuel series is -48.5˚C for FB40S2.

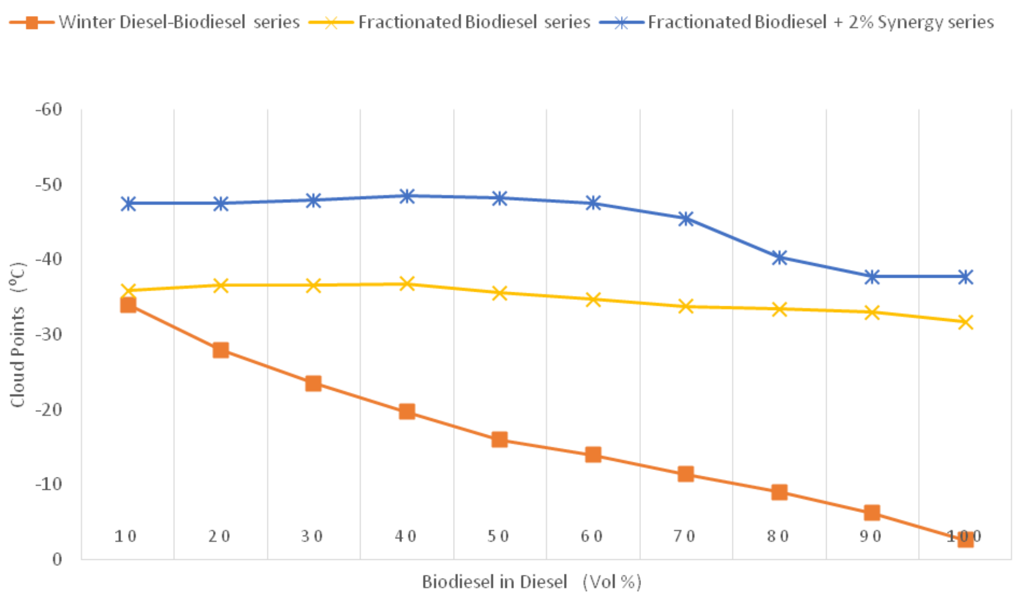
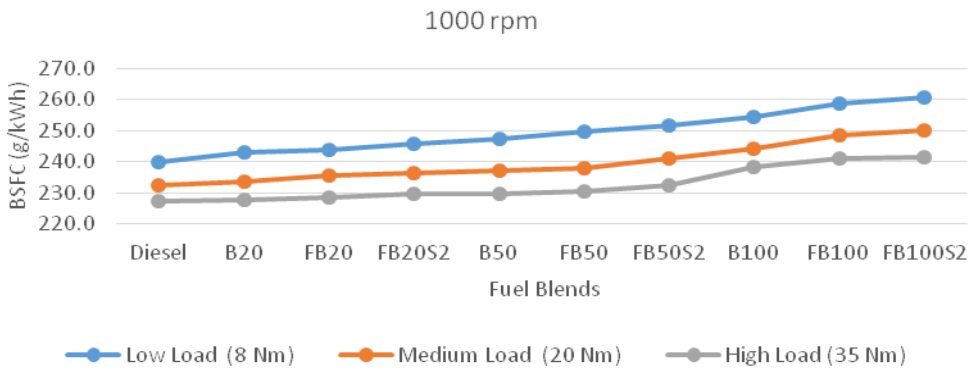


Figure 3. Variation of biodiesel content in diesel fuel and corresponding cloud points.

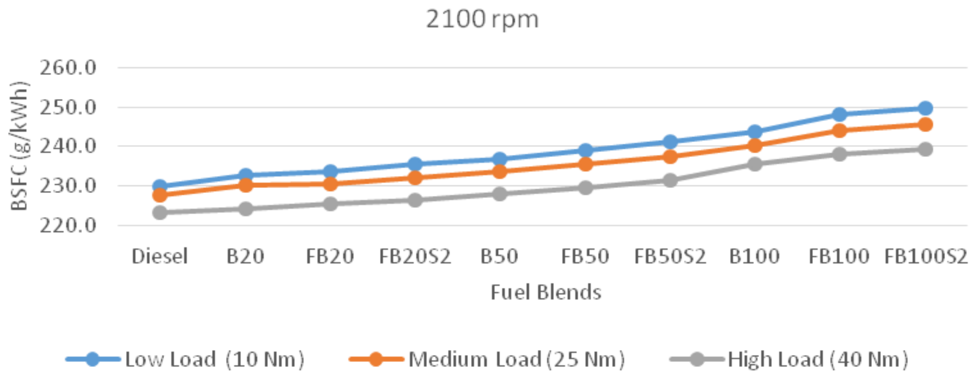
3.2 Engine performance

3.2.1 Brake specific fuel consumption (BSFC)

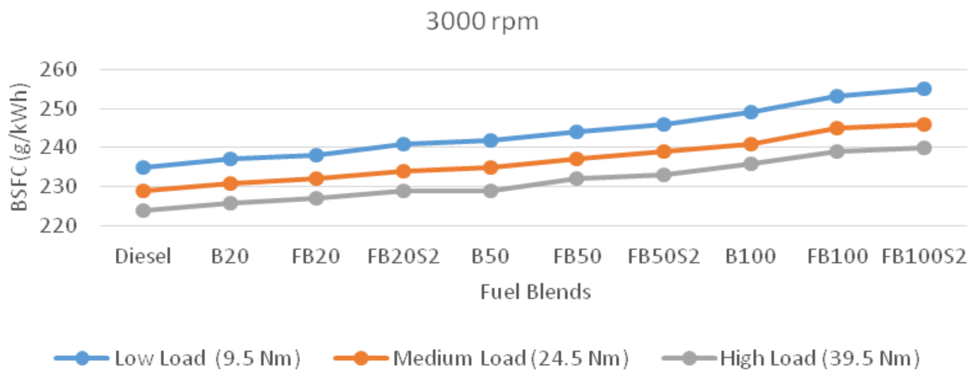
The variation of BSFC for all tested fuels with respect to engine speed and load is depicted in Figure 4. It was observed that the BSFC of biodiesel was generally higher compared to diesel fuel. Biodiesel normally possesses lower heating value because of its fuel-borne oxygen. High fuel consumption can be attributed to the lower heat content of biodiesel blends.



(a)



(b)



(c)

Figure 4. BSFC values at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.

At 1000 rpm, BSFC value was maximum compared to other rpm condition at similar loads. BSFC decreased at 2100 rpm and then increased slightly at 3000 rpm due to frictional loss increases and volumetric efficiency decreases compared to lower speed. Figure 4 also showed decrease in BSFC as the load was increased. At lower loads, very less fuel is injected into the combustion chamber resulting in lowered cylinder pressure and temperatures. With increase in load, more fuel enters the combustion chamber resulting in elevated temperatures which help better combustion reduce the BSFC gradually. The respective average BSFC of B20, B50 and B100 at high, medium and low load conditions are 234, 237 and 244 g/kWh, respectively at 1000 rpm, 229, 232 and 238 g/kWh at 2100 rpm, and 231, 235 and 241 g/kWh, respectively at 3000 rpm. Overall, FB100 and FB100S2 increase BSFC the most at all loads due to lower heating value compared to other fuel blends. The average minimum BSFC value at variable engine speed for the blend with additives (FB20S2) was 240, 234 and 228 g/kWh at low, medium and high loads; and without additive (FB20) it was 237, 233 and 224 g/kWh at low, medium and high loads.

3.2.2 Brake Thermal Efficiency

Brake thermal efficiency (BTE) is a parameter that determines the transformation of heat energy to useful work. Even though biodiesel blends have higher BSFC, the efficiency of the blends is also higher than diesel fuel because of better combustion due to higher oxygen content in the blends. The results indicate that biodiesel blends are better than diesels at all load conditions, and inherent oxygen of biodiesel can enhance the combustion process. It is observed from Figure 5, that there is an increase of BTE for all fuel blends with increasing loads. This is due to increase of average combustion temperature at higher loads, which can facilitate better combustion.

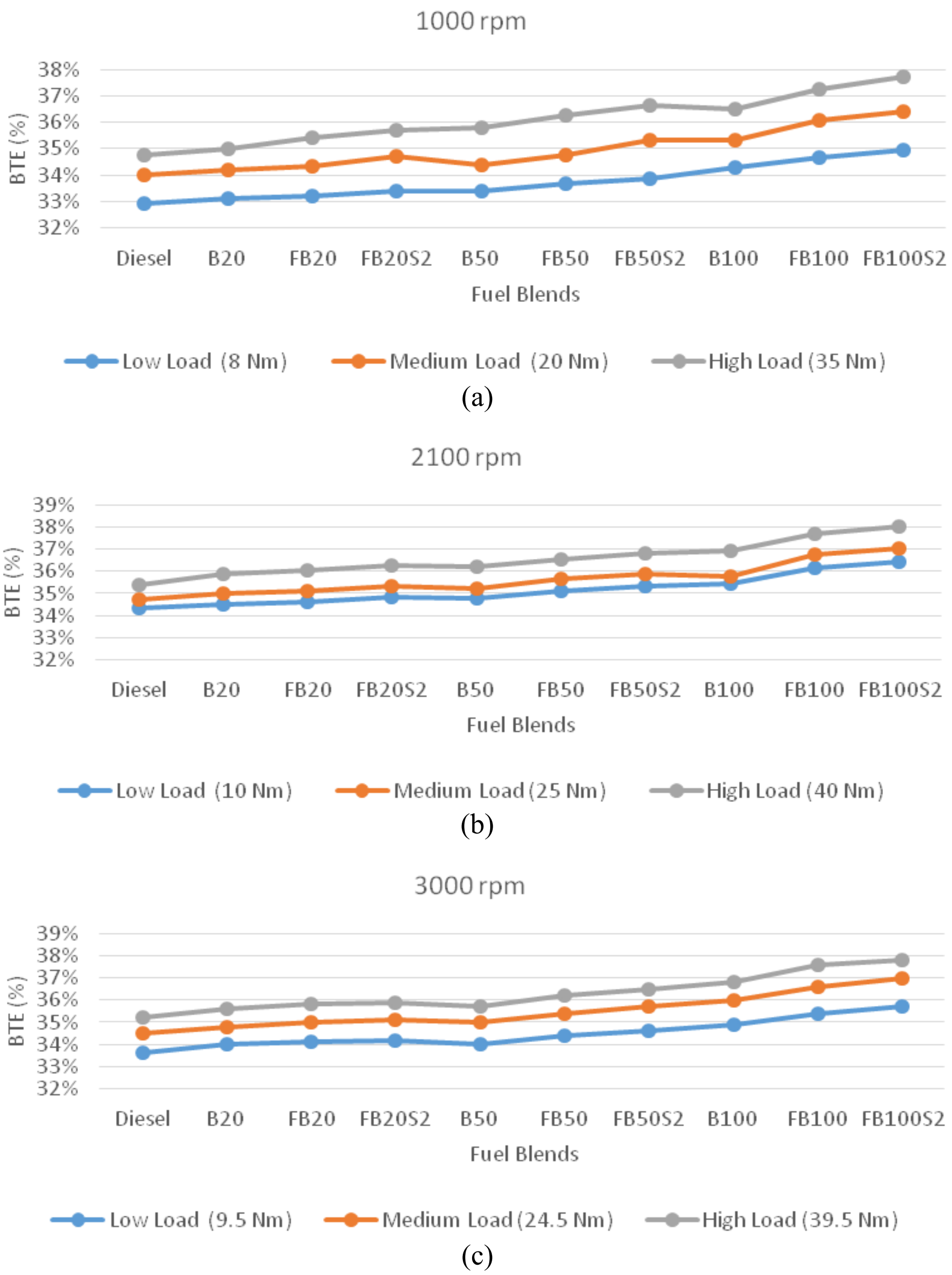


Figure 5. BTE values at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.

Test results showed that BTE increased with increasing engine speed of the engine from 1000 rpm to 2100 rpm due to better atomisation and fuel-air mixing with increase in speed and then reduced slightly for 3000 rpm. Furthermore, the higher efficiency with fractionated biodiesel-diesel blends than diesel indicates that combustion with fractionated biodiesel-diesel blends is better than diesel fuel combustion. This is attributed to higher oxygen content of fractionated biodiesel. Therefore, low emission of CO and HC are expected due to better combustion with fractionated biodiesel, which will be discussed in the following subsection. On an average, pure biodiesel has about 4.8% higher efficiency at low load condition, about 5.7% under medium load, and about 5.4% under high load operation at 1000, 2100 and 3000 rpm, respectively. The average increase of BTE was 5%, 6% and 6.4% with respect to diesel fuel for FB100 for low, medium and high loads, respectively. Similarly, for FB100S2, the average increase of BTE was 5.8%, 6.6% and 7.3% for low, medium and high loads, respectively.

3.3 Engine emissions

3.3.1 CO emissions

Figures 6(a)-6(c) illustrate the CO emissions at different engine loads and speeds for various fuel blends. Average CO emissions over the testing period from different blends were compared to those of conventional diesel fuel. It was found that higher biodiesel content causes higher reductions in CO emissions. This was due to higher oxygen content in the biodiesel compared to diesel fuel which results in more efficient combustion compared to diesel fuel.

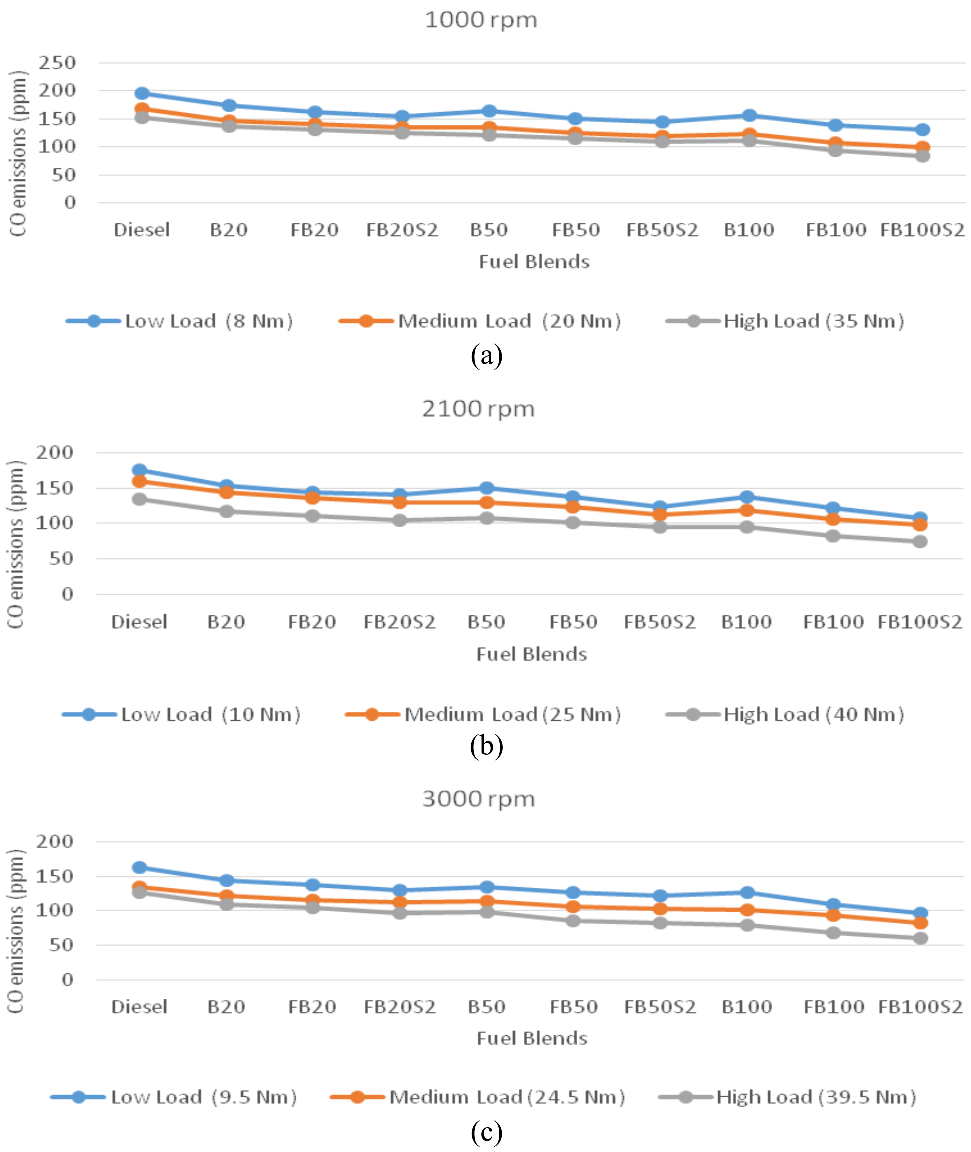


Figure 6. CO emissions at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.

In addition, engine load was proved to have a big effect on CO emissions. The results showed decrease of CO emissions with higher engine loads. This could be due to the fact that air-fuel mixture has lower temperature at low load conditions leading to higher CO emissions than at high loads. It was also observed that all the blends had lower CO emission than diesel fuel all-over the engine speed range, which decreased with the increase of engine speed. With 2% Wintron Synergy in fractionated biodiesel-diesel blend, additional fuel-bound oxygen in the blends ensured CO oxidation further, which helped reducing more CO emissions. FB100S2 produced the lowest CO emissions at all load and speed conditions. All the fractionated biodiesel-diesel-synergy blends generated slightly lower CO emission with that of fractionated biodiesel-diesel blends. Average CO emissions for FB100S2 were 92, 80 and 71 ppm, respectively at 1000, 2100 and 3000 rpm at different engine loads.

3.3.2 HC emissions

HC emissions at different engine load and speed for different biodiesel fuel blends is illustrated in Figure 7. Unburned hydrocarbon originated from various sources in the cylinder during combustion. Generally in a diesel engine, HC emission was mainly due to reasons such as fuel trapping in the crevice volumes of the combustion chamber, low temperature bulk quenching of oxidation reactions, locally over lean or over rich mixture, liquid wall films for excessive spray impingement, and incomplete fuel evaporation. Oxygenated compounds in biodiesel reduced the HC emission significantly in all the biodiesel blends as can be seen in Figure 7.

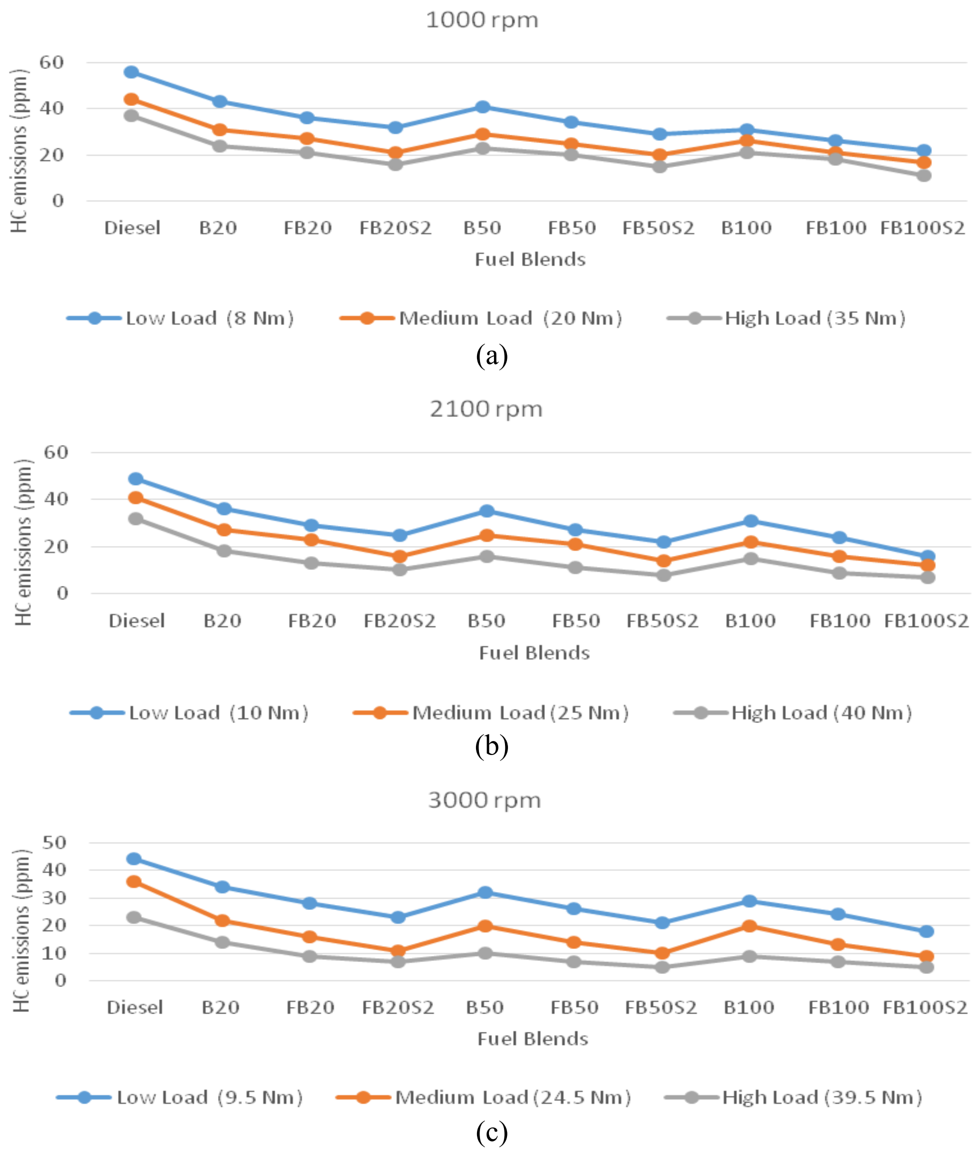


Figure 7. HC emissions at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.

At 1000 rpm under low load condition, HC produced from different fuel blends was 56 ppm from diesel, 43 ppm from B20, 36 ppm from FB20 and 32 ppm from FB20S2. Increasing the engine load and speed reduced HC emissions slightly for all fuel blends. At 1000 rpm, HC emissions for B20 reduced on an average of 30%, 42% and 54% under low, medium and high load, respectively. At 2100 rpm, HC emissions for B20 reduced on an average of 36%, 52% and 77% under low, medium and high load, respectively. At 3000 rpm, HC emissions for B20 reduced on an average at 29% under low load, 64% under medium and high loads. When engine speed was at maximum, all fuels showed a reduced amount of HC emissions compared to lower engine speed .

With increasing amount of fractionated biodiesel in blends, unburned HC emissions were lower than diesel fuel. These reductions can be attributed to the higher oxygen contents of fractionated biodiesel and synergy in the blends. It was noticed that at all engine loads and speeds, FB100S2 produced the least amount of HC emission as compared with other fuel blends. FB20S2 produced 32, 21 and 16 ppm of HC emission at 1000 rpm under low, medium and high load, respectively. At 2100 rpm, FB20S2 produced 25, 16 and 10 ppm of HC emission under low, medium and high load, respectively. Similarly at 3000 rpm, FB20S2 produced lower HC emissions measuring 23, 11 and 7 ppm of HC emission under low, medium and high loads.

3.3.3 NOx emissions

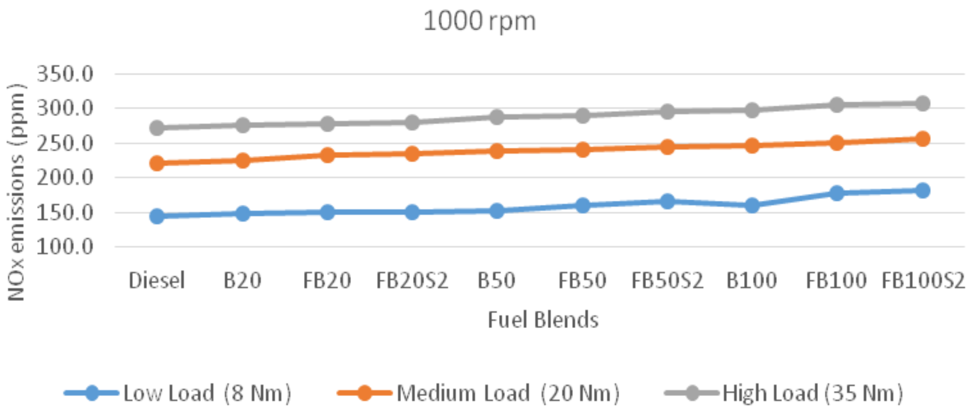
Figure 8 shows the NOx emissions for different biodiesel blends with the variations of engine loads and speeds. All biodiesel blends produced higher amount of NOx emission than that of diesel fuel. The NOx emissions of biodiesel blends were gradually increased with the increase in concentration of normal biodiesel and fractionated biodiesel in the blends, and with the increase in engine loads. However, NOx emissions decreased with increase in engine speed, possibly due to leaner combustion. With increase in load, exhaust temperature was increased, which was an indication of high in-cylinder temperature combustion. Consequently, NOx was increased at higher loads. However with increase in engine speed, no increase of exhaust temperature was recorded.

The maximum amount of NOx emissions (308 ppm) was found with fractionated biodiesel with 2% Wintron Synergy at 1000 rpm under high load. Fractionated biodiesel with 2% Wintron Synergy series produced higher NOx emissions compared with biodiesel series because synergy has oxygen content in it. At low load conditions, B20 produced much lower NOx emissions at all engine speeds compared with other biodiesel blends. Diesel fuel produced least NOx emissions at all loads and speed compared to other fuel blends. At 3000 rpm, diesel produced 105 ppm of NOx emission compared to 145 ppm at 1000 rpm under low load. Similarly for pure biodiesel, NOx emission was 228 ppm at 3000 rpm compared to 298 ppm at 1000 rpm under high load condition.

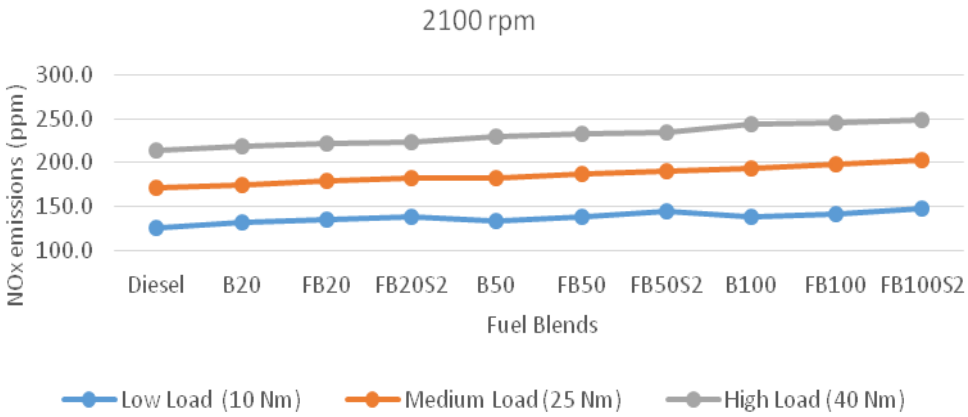
3.3.4 Smoke opacity

Figure 9 shows the exhaust smoke opacity for biodiesel blends at different engine loads and speeds. Soot content in the exhaust gas was indicated by the smoke opacity, therefore this parameter can be correlated with fuels tendency to form soot during combustion. They are mainly formed due to incomplete combustion of hydrocarbon fuel. The composition of smoke generally depends on engine operating conditions and different fuel properties.

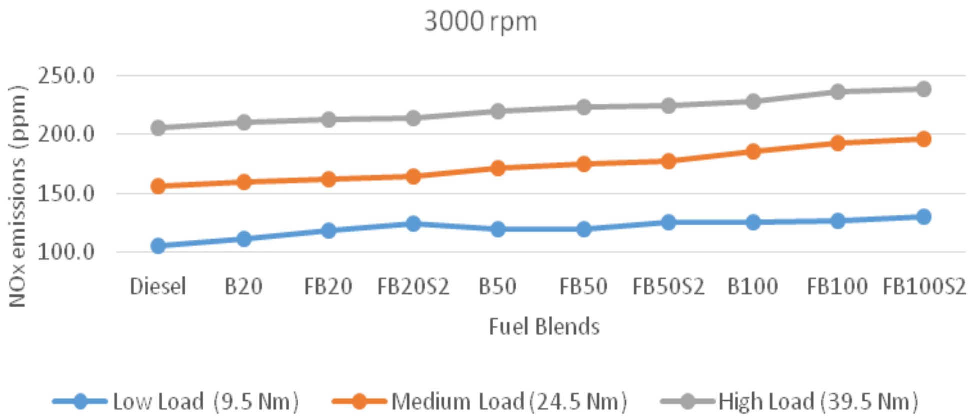
It can be observed that, smoke opacity values were quite lower than diesel for all biodiesel blends with increase in biodiesel content. Higher oxygen and lower sulfur content in normal biodiesel and lower amount of saturated fatty acid compounds in fractionated biodiesel are responsible for this decrement. Application of oxygenated additives enhanced the decrement even further. In Figure 9 (a), (b) and (c), it can be seen that 2% Wintron Synergy additive blends had lower smoke opacity than corresponding fractionated biodiesel blends. It can be attributed to the extra fuel-bound oxygen of the blends with synergy which assisted the combustion to be leaner. Fractionated biodiesel blends generated higher reduction against the corresponding normal biodiesel blends, which can be attributed to considerable lower saturated compounds present in fractionated biodiesel compared to normal biodiesel, causing a better atomization of the corresponding blends. Increasing the engine speed helped in reduction of smoke opacity emissions due to lean combustion. The average smoke opacity emission for FB20S2 was 3.4%, 2.2% and 1.5% at 1000, 2100 and 3000 rpm, respectively. For FB50S2 at 1000 rpm, the smoke opacity was 2.1%, 3.2% and 3.9% under low, medium and high load, respectively. Similarly for FB50S2 at 2100 rpm, smoke opacity was 1.7%, 2.3% and 2.9% under low, medium and high load respectively. Finally at 3000 rpm, smoke opacity for FB50S2 was 1.2%, 1.3% and 1.9% under low, medium and high load, respectively. However, with increase in load, smoke opacity increased slightly at all engine speed; this could be due to the fact that large amount of fuel was injected into the combustion chamber resulting in higher pockets of fuel, which may not involve in combustion process and emit high amount of smoke. At 1000 rpm, FB100S2 reduced smoke opacity by 50% under low load, 48% under medium load and 41% reduction at high load compared to diesel fuel. At 2100 rpm, FB100S2 reduced smoke opacity by 40%, 29% and 25% under low, medium and high load, respectively. Similarly at 3000 rpm, 18%, 16% and 23% reductions in low, medium and high load, respectively were obtained.



(a)

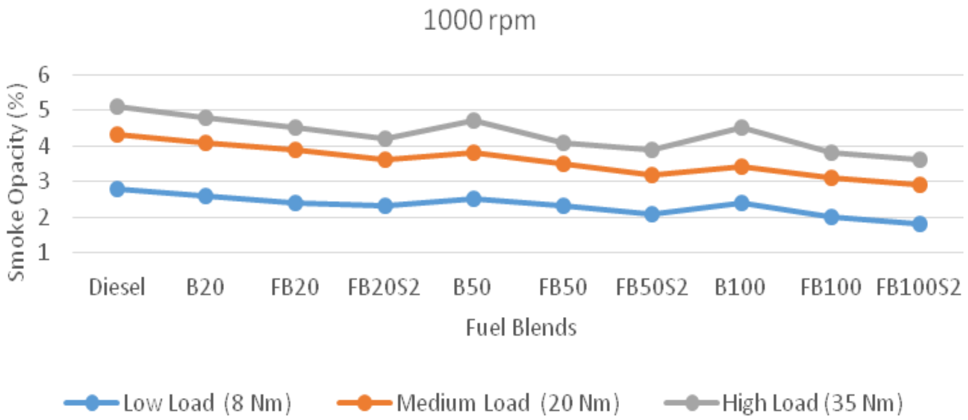


(b)

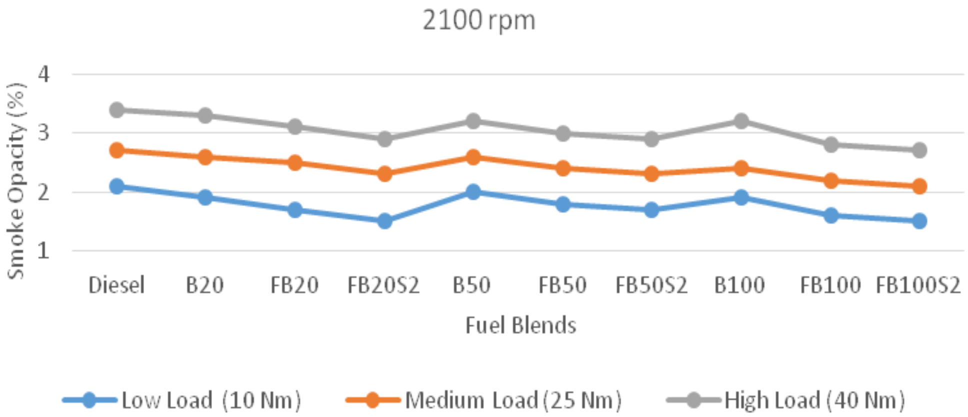


(c)

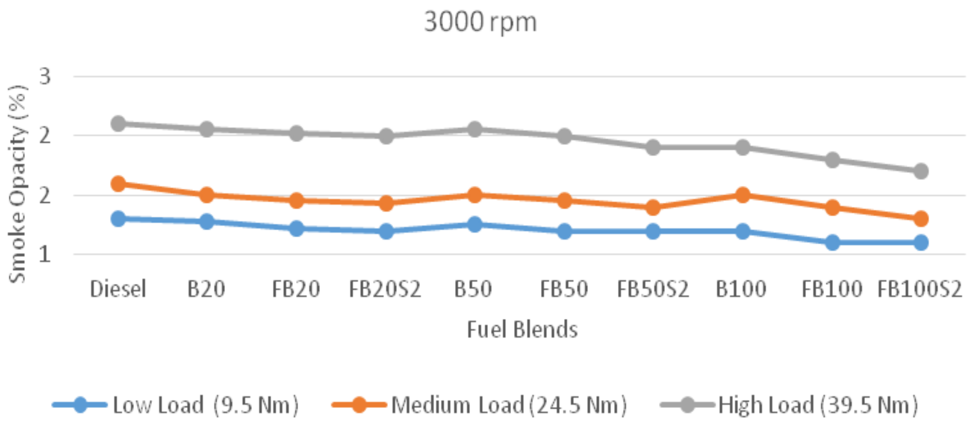
Figure 8. NOx emissions at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.



(a)



(b)



(c)

Figure 9. Smoke opacity emissions at (a) 1000 rpm (b) 2100 rpm (c) 3000 rpm for different fuel blends under variable engine loads.

4. Conclusions

In this study, an experimental investigation was conducted to explore the performance and emissions of different normal biodiesel blends and fractionated biodiesel blends with cold flow improver Wintron Synergy on a light-duty DI diesel engine. Conclusions from these test results are summarized below.

1. The CPs of fractionated biodiesel blends were significantly lower than the CPs of normal biodiesel blends. Moreover, CPs of fractionated biodiesel blends with 2% Wintron Synergy were further lower than fractionated biodiesel blends. It was found that fractionated biodiesel up to 80% fractionated biodiesel with 2 vol% of Wintron Synergy in winter diesel is most suited to be used in extreme cold weather conditions.

2. Compared to diesel fuel, all the biodiesel fuel blend series increased BSFC, and 2100 rpm shows the lowest BSFC. BTE was inversely proportional to BSFC, and BTE increased with biodiesel content in fuel blend similar to the BSFC trend.
3. CO emissions for all fuel blends were lower at high load condition at each rpm. The higher the biodiesel percentage in biodiesel-diesel blends, the lower the CO emissions from low to high load conditions. Maximum reduction of CO emissions at variable engine load and speed was achieved by FB100S2, measuring an average of 72% lower emissions than diesel fuel.
4. HC emissions for all fuels were lower at high loads at different engine speeds. The HC emissions showed reduction with increase in engine speed. The higher the biodiesel percentage in biodiesel-diesel blends, the lower the HC emissions, a similar trend to that of CO emissions. In light duty diesel engine at variable engine loads and speeds, average HC emissions were the lowest for fractionated biodiesel blends with synergy.
5. The highest NOx was emitted at high load at 1000 rpm with fractionated biodiesel. NOx emissions increased with increase in biodiesel content in fuel blends. However, there was reduction in NOx formation when engine speed was increased. Under variable engine load and speed, B100 produced an average NOx increase of 14%, 12% and 10% with low, medium and high load, respectively. Similarly with FB100S2, average NOx increase was 18%, 16% and 13%, respectively at low, medium and high load.
6. All the fuel blend series reduced smoke opacity at all engine load and speed conditions than diesel. In this engine under variable engine load, smoke opacity decreased with increase in biodiesel percentage in the blends. All the fuel blend series increased smoke opacity with higher engine load and decreased with increase in engine speeds. With FB100S2, the lowest average smoke opacity emissions were obtained, which were 1.6%, 2.3% and 2.9% at low, medium and high load, respectively.

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