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ORIGINAL ARTICLE

The Impact of Biodiesel Blend Variation Contamination to Engine Friction, Wear, Performance and Emission

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ABSTRACT – Biodiesel can be utilised in diesel engines without major alteration to the engine; however, its use can lead to engine oil dilution through biodiesel leaking and scraping to the engine oil pan. The objective of this research is to investigate the contamination of biodiesel in engine lubricant oil, and determine the relationship between engine performance and emission for three different blends of palm methyl ester (B10, B20, and B30). To simulate the contamination, the engine oils were blended with biodiesel fuels at 5%, 10%, 15% and 20% by volume and these mixtures were tested on four-ball test equipment. An air-cooled diesel engine was used to analyse the influence of the three biodiesel blends on the output and emission of the diesel engine. The results show that both coefficient of friction and wear scar diameter increased with the increase of biodiesel percentage. The results of engine performance during both sweep test and step test showed that the variation of torque and power among the blends at a particular speed was within a very narrow range.

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INTRODUCTION

The rapid depletion of fossil fuel, significant population growth and changes in lifestyle intensify the need for governments to take steps to reduce their reliance on traditional hydrocarbon fuel and gas [1]. There is a need for alternative energy sources to enable this move from conventional fossil fuels. Biodiesel, a mono-alkyl ester of long-chain fatty acid, is one of the alternative renewable fuels being studied, is derived from vegetable oils or animal fats through esterification or transesterification reactions with small chain alcohols such as methanol and ethanol [2]. Throughout the last decade, the production and consumption of biofuels have increased rapidly throughout the world which is from 16 billion litres in 2000 to over 100 billion litres in 2011, in an effort to reduce greenhouse gas emissions, diversify transport fuels, promote renewable energy and create jobs, particularly in rural areas and developing countries [3].

Based on the available literature, global primary energy consumption rose by about 2.3% in 2013 compared to 2012 amid slow global economic growth. In addition, all fuels consumption and output increased to record levels for each type of fuel except nuclear power. Global fuel consumption has risen faster than any form of fossil fuel production. The data suggest that growth in global carbon dioxide (CO_2) from energy use also increased in 2013, though it remained below average [4]. In addition to the depletion of crude oil reserves, uncertainty of fossil oil prices, along with growing concern about greenhouse gas emissions, which raises the global warming problems, have increased calls for of global energy economy adoption based on renewables [5], [6].

Furthermore, rapid growth in the global motor industry has led to a rise in harmful emissions of pollutants to the earth. It is very important to note that around 22 % of global greenhouse gas (GHG) emissions come only from the transportation sector. The study conducted by the International Energy Agency (IEA) predicted that GHG (carbon dioxide) emissions from the transport sector rose by 92% between 1990 and 2020, which will release 8.6 billion metric tons of carbon dioxide (CO_2) into the atmosphere between 2020 and 2035. As of 2012, data shows that 42.4 million tons of CO_2 were emitted by the transport sector in Malaysia. In the coming years, an increased number of registered motor vehicles is expected, which increasing the emissions further. It is also known that CO_2 emissions rose from about 15 million metric tons in the early 1990s to 42.43 million metric tons in 2012 [7].

Biodiesel is becoming increasingly popular among renewable energy sources these days because it has better qualities compared to traditional diesel fuels, such as renewability, higher flash point, biodegradability, better lubricity and lower greenhouse gas emissions like HC, CO and particulate matter. Research showed that diesel engines fuelled by palm oil could reduce carbon monoxide, sulfur oxide, hydrocarbon, smoke, and particulate matter (PM) emissions [4]. Studies by Ganjehkaviri et al. [8] showed that as the volume percentage of palm biodiesel rises in a blend, emission formation decreases. Lopes et al. [2] found that increasing concentrations of biodiesel in the fuel will decrease the NO and particulate matter emissions. Biodiesel also has some drawbacks in view of these positive aspects that hinder its commercialisation. The major drawback of biodiesel is the presence of a higher level of unsaturated fatty acids components in its structure, which are corrosive and attack metals, causes injector coking, carbon deposition, and auto-oxidation [9]. This can lead to

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excessive friction and wear of various moving parts, such as cylinder liners, bearings, cams, tappets, crankshaft journals, pistons and piston pins, valve guides and valve systems [10]. Dwivedi et al. [11], Vedaraman et al. [12], Yusop et al.[4] and Chattopadhyay et al. [13] reported higher brake specific fuel consumption (BSFC) when using biodiesel compared to neat diesel, and BSFC increased as blend ratio increased. At the same time, BMEP was slightly lower than that of mineral diesel. Currently, a single solution for the different types of biofuels is needed. The role of base oil chemistry and additives, as well as tribo-active materials, are featured to deal with the antagonistic effects of biofuels [14].

Nevertheless, studies have found that biodiesel blends up to 20% with the conventional diesel fuel can significantly reduce tribo-contact surface wear and friction coefficient [15], [16]. For this reason, laboratory tests were conducted to get an idea of the tribological activity of B20. Hence, the objective of this paper is to study the tribological effects of B10, B20 and B30 palm oil biodiesel blends by investigating the impact of engine oil dilution and degradation on wear characteristics of engine components. Finally, the study also investigates B10, B20, and B30 blends on engine performance and emission.

METHODOLOGY

Tribology Test

In this study, a four-ball wear test had been used to investigate the impact of engine oil dilution and degradation of B10, B20 and B30 blends, and also to investigate the influence of biodiesel blends on wear characteristics of the diesel engine. The engine dynamometer test had been used to determine the impact of B10, B20, and B30 blends on engine performance and emission.

Oil dilution was conducted to prepare samples used to study the tribological effect of biodiesel-engine oil contamination using the four-ball test method by evaluating the anti-wear performance of B10, B20 and B30 biodiesels blended with engine oil. To mimic contamination, biodiesel of B10, B20, and B30 were each blended with engine oils in a percentage of 5%, 10%, 15%, and 20%, respectively. Four ball wear test was performed according to ASTM D 4172, where a steel ball was rotated against three lubricated stationary steel balls under a specified load, speed temperature and time by conforming to ASTM D 4172 test standard. During the experiment, new balls were used for each run and were thoroughly cleaned with acetone together with clamping parts and an oil cup. One of the cleaned balls was inserted into the ball chuck, and the ball chuck was inserted into the spindle of the four-ball test machine and tightened accordingly. The remaining three balls were inserted into a ball cup and locked the balls in position by starting with hand tightening, then by a torque range to a torque of 50 Nm. Then the ball cup was filled with diluted oil samples to the recommended level. Then the ball cup assembly containing the three balls was placed on the test machine, after which it was loaded smoothly. The four-ball test machine was connected to a computer to record friction torque.

The values of the coefficient of friction (COF) was calculated from the recorded friction torque data using the Eq. (1) [17]:

$$COF = \frac{T\sqrt{6}}{3Wr} \tag{1}$$

where T is friction torque (kg/mm), W is applied load (kg), r is the distance from the centre of the contact surfaces on the lower balls to the rotation axis, which was 3.67 mm

To determine the wear characteristics, scar wear diameters of the three lower balls and their surface roughness were measured using an optical microscope on 3D non-contact profilometer where the average diameter and roughness were reported, respectively.

Engine Performance and Emission Test

The performance and emission characteristics of three brands of biodiesel, B10, B20, and B30 were tested on a single-cylinder four-stroke, air-cooled direct injection diesel engine named LAUNTOP supplied by KHENG SUN. The process of determining fuel performance was done by connecting the engine to DYNOmite Engine Dynamometer, while the exhaust gas emissions were measured by model 5002 Exhaust Gas Analyzer. Sweep test and step test were carried out to determine both performance and emission characteristics of each fuel. Detailed engine specifications are given in Table 1, while the experimental set up is given in Figure 1.

Before conducting a new test for each fuel, the fuel tank was drained of its previous fuel used for testing, and the tank was flashed with the next test fuel. After flashing, the tank was filled with the test fuel. Thereafter, the engine was run for about 15 minutes before the test runs for actual data collection to ensure that the engine is circulating only the test fuel and also ensuring that data is collected when the engine is running at optimum temperature.

During the sweep test, the engine speed started from 2000 rpm and finished at 3000 rpm with full throttle opening, while during the step test the engine speed started at 2000 rpm and ended at 3500 rpm, with a step increment of 250 rpm. In both cases, the recorded power (hp) and torque (Nm) were used to determine the engine performance of each biodiesel blend.

Emission was measured by an exhaust gas analyser of model 5002, where exhaust gas samples were transferred from the exhaust tail to the analyser by inserting a probe at the end of the exhaust pipe. All data were collected and stored using the engine dynamometer data acquisition computer.

Table 1. Engine specifications.

MODEL	Diesel 170FA	
Bore*stroke (mm)/(inch)	70×57 2.76×2.24	
Displacement (cc)/(cu.in.)	219/13.36	
Engine speed (rpm)	3000	3600
Maximum output (kW)/(hp)		2.8/3.8
Continuous output (kW)/(hp)	2.5/3.4	
Mean effective pressure (kPa)	425	
Power take-off	Crankshaft or camshaft (camshaft PTO rpm is 1/2)	
Starting system	Recoil or recoil/electric	
Fuel tank capacity (L)/(us.gal)	2.5/0.66	
Lube oil capacity (L)/(us.gal)	0.75/0.20	
Dimensions L×W×H (mm)/(inch)	332×392×416 13.0×15.4×16.3	
Net weight (recoil) (kg)/(lbs)	27/59.5	
Cooling type	Force air-cooled system	

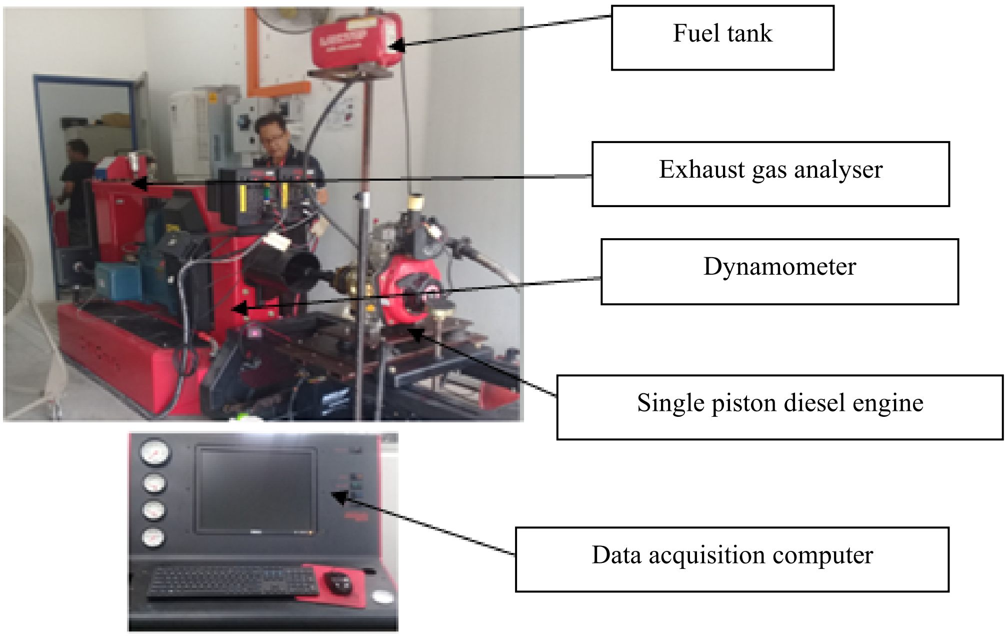

Figure 1. Engine dyno set-up.

RESULT AND DISCUSSION

Coefficient of Friction

Figure 2 illustrates the variation of coefficient of friction with respect to time for percentage volume of 20W50 semi-synthetic engine oil diluted with B10, B20 and B30 palm oil biodiesel respectively at a ratio of 5%, 10%, 15%, 20%, compared with undiluted engine oil. From Figure 2(a), it can be noted that 5%, 10% and 15% dilution had unnoticed run-in period, which is a transient period when the contacting surfaces of bearing balls undergo a continuous change of the micro-topography before the lubricant is able to reach the steady operating state [18], followed by 0%, 20% which had a run-in period of less than 800 seconds. Generally, it is noted that the coefficient of friction increases with an increase in percentage dilution where the 5% and 10% dilution graphs were lower than the reference 0% dilution while 15 % and 20% graphs were higher than the reference, with 10% and 15% dilution closer to 0% dilution.

The sharp increase after 2850 seconds for 20% dilution indicates that lubrication failure was about to happen. This was because the 20% dilution caused a significant reduction in engine oil viscosity and ultimately reduced the thickness of the oil film separating the interacting surfaces, thereby reducing the load-carrying capacity of the lubricated contact surfaces. This leads to higher friction, which encourages substantial material wear.

Figure 2(b) and Figure 2(c) show the coefficient of friction variation for B20 and B30 engine oil dilution similar to B10 dilution, indicating that the coefficient of friction increases as the dilution percentage increases. However, the only difference is that for B20, only the graph for 5% dilution is less than the reference oil of 0% dilution. In comparison, B30 dilution percentages all graphs for the coefficient of friction are higher than the reference at 0% dilution. Additionally, it is noted for B30 dilution in Figure 2(c) that lubrication failed at 2820 seconds for 15% dilution. Several factors that might have led to this failure include the insufficient volume of lubricant leading to boundary condition starvation, metal fatigue from improper metallurgy, rough surfaces, and imbalance of loading.

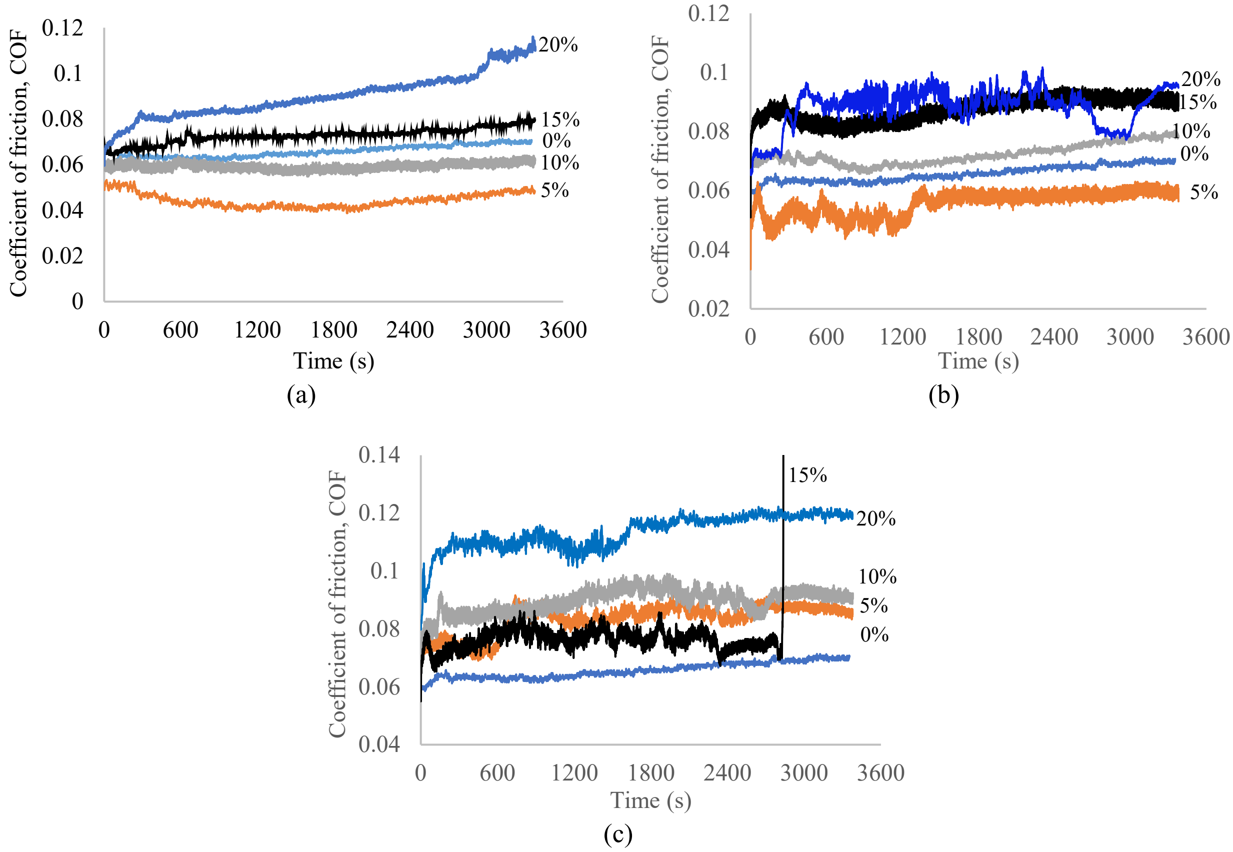

Figure 2. Coefficient of friction variation for (a) B10 diluted 20W50 engine oil (b) B20 diluted 20W50 engine oil, and (c) B30 diluted 20W50 engine oil.

Wear Scar Diameter

Figure 3 shows the average scar wear diameter of lower balls from the four-ball tests for different percentages of B10, B20 and B30 engine oil dilutions. The images measured by the optical microscope on 3D non-contact profilometer. Figure 3 generally shows that wear scar diameter is found increasing with the increase of both biodiesel blend ratio and increase of percentage dilution. However, for B10 engine oil with 10% dilution and 15% dilution had the same scar wear diameter of 0.36 mm, which was closer to 0.37 mm scar diameter for 0% dilution, while 5% dilution had 0.38 mm. Out of all blends, 20% dilution registered the highest wear scar diameter compared to the rest.

The graph also demonstrated that contamination of engine oil by B10 and B20 palm oil biodiesel at 10% and 15% have a lower engine oil degradation, hence minimum wear characteristics compared to 5% and 20%. This is in contrast to 20%, which indicates increased wear compared to undiluted engine oil. The increased scar wear diameter was due to a higher percentage of fuel dilution in the engine oil, which would have reduced the viscosity of the engine oil, diluted the anti-wear additives of engine oil, and possibly also reacted with additives. However, there is much disarray among researchers concerning whether biodiesel dilution aides or ruins the oil lubricity as both have been accounted for as being valid. The decrease of the anti-wear additives' usefulness rivals the improved lubricating capacity of biodiesel; however, in the end, one must dominate over the other.

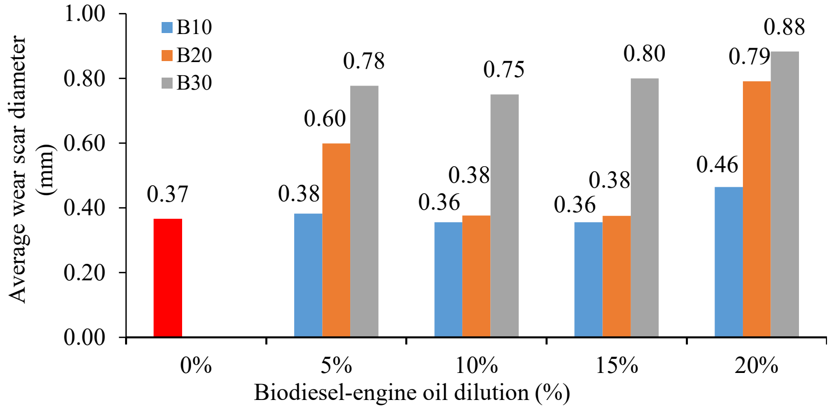

Figure 3. Wear Scar Diameter (WSD) for various 20W50 engine oil dilution.

Figure 4 shows the relationship between the coefficient of friction, wear scar diameter and biodiesel-engine oil dilution. The graph was plotted from the average of both wear scar diameter and the average coefficient of friction of each biodiesel blend. It is noted that the coefficient of friction and wear scar diameter increased with the increase of biodiesel concentration. The increasing trend of the coefficient of friction almost follows the increasing trend of wear scar diameter, as shown in Figure 4.

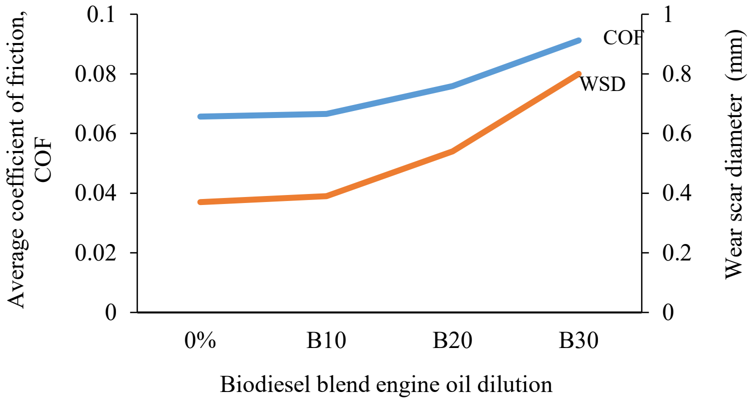

Figure 4. Coefficient of friction and wear scar diameter vs biodiesel blend ratio.

Surface Roughness

It is noted from Figure 5(a) that the surface roughness increases with an increase in blending ratio at each dilution percentage, with 10% and 15% dilution showing lower surface roughness. Overall, B10 and B20 show better surface protection compared to B30. While in Figure 5(b), it is noted that surface roughness increases with an increase in percentage dilution, which indicates that engine oil surface protection decreases with increased fuel contamination.

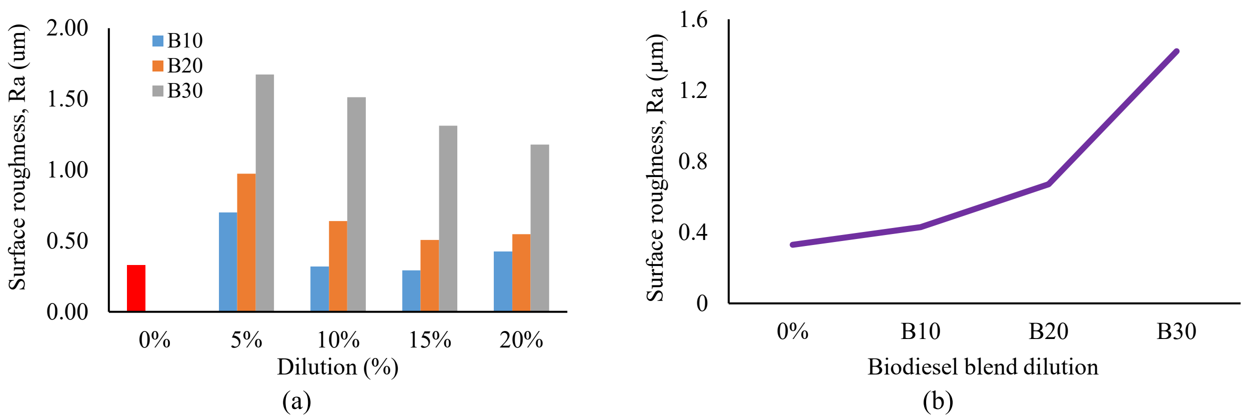

Figure 5. Roughness of Ra comparator showing an average profile for various dilutions.

Engine Performance

Figure 6 shows variations in the power and torque output with the engine speed for all three fuels tested for the sweep test. From section A and section C of the graph in Figure 6, it can be noted that both power and torque does not linearly depend on biodiesel percentage. For example, at the speed range of 2050 and 2100 rpm, and between 2250 and 2300 rpm, the graph shows that both power and torque increase with increasing biodiesel percentage. At the speed of 2130 rpm and 2170 rpm, the B20 shows the highest power and torque, seconded by B30 and then B10, while at 2200 rpm, B10 yields better performance than B20 and B30, with B30 having the lowest. From section B of the graph in Figure 6, it can be noted that both power and torque linearly depend on biodiesel percentage, with B10 and B20 graphs following a similar profile with their values close to each other. It is noted that B30 has an overall better power output, with B10 and B20 almost tying in in this section.

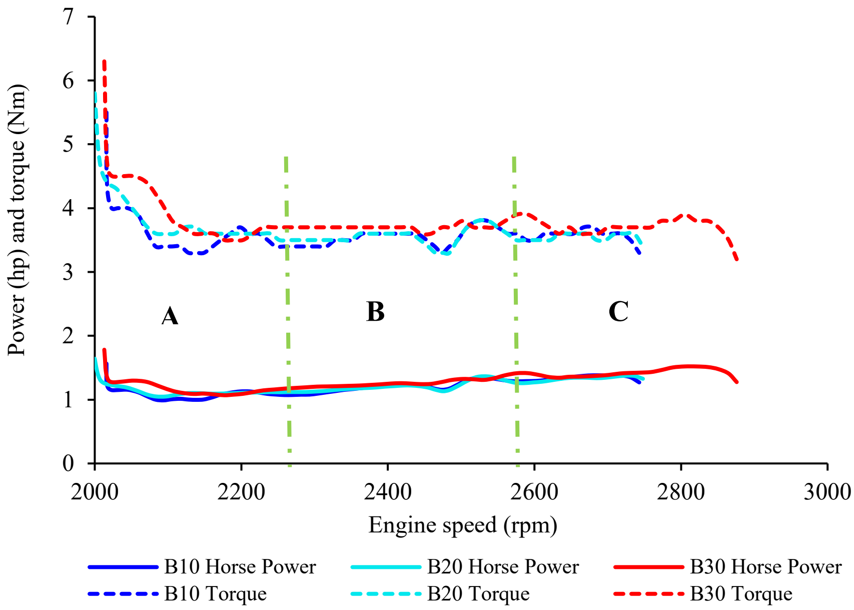

Figure 6. Variation in power and torque with engine speed during sweep test.

It is observed from section A in Figure 7 that B30 has the highest torque and power within this entire range with a peak of 6.4 Nm and 2.0 hp, respectively. The peak torque for B10 and B20 is 6.1 and 5.9 Nm, respectively, while the peak power values of B10 and B20 are 1.9 and 1.86, respectively. It is also noted that before the first step, B10 have higher magnitude values of both torque and power; however, after the step, B20 have a higher magnitude value of both power and torque than B10.

The results from Figure 7; section B shows that B30 has the highest magnitude of torque and power of 6.7 Nm and 2.6 hp. This is followed by the peak values of B20, with B10 having the lowest peak values for power and torque. It is also noted that the magnitudes for B20 are greater than B10 during and after each step, after which B10 magnitudes become higher than that B20 before the next step.

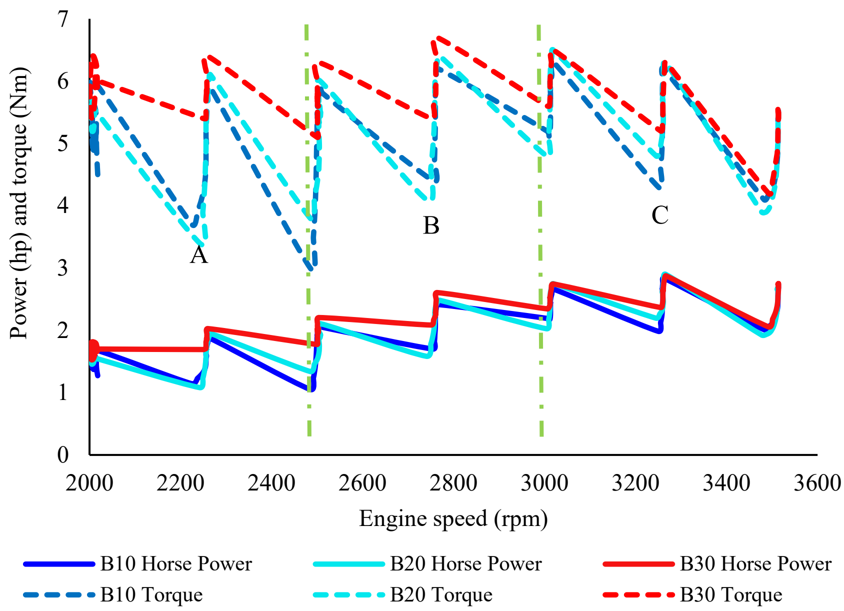

Figure 7. Variation in power and torque with engine speed during step test.

From section C of Figure 7, the results show that all blends have comparable torque and horsepower peak performance. It is noted that the magnitudes of both torque and power during the first step corresponding to the increase in biodiesel blending ratio, with B10 having the lowest value and B30 is the highest, and B20 is in between. However, during the second step, B10 has higher values than B20, with B30 having the highest values.

Emission

The comparison of CO_2 emission using both the sweep test and step test for all the three tested fuels is presented in Figure 8. It is noted that CO_2 emission increases with an increase in biodiesel blending ratio during the sweep test, while for the step test, the CO_2 emission for B30 was lower than B20 but higher than B10. In both cases, it is noted that CO_2 emission reduced with an increase in engine speed because increasing engine speed fosters a decrease in the air-fuel ratio inside the engine. On the other hand, the surge in CO_2 emission with an increase in the blend ratio of biodiesel is due to a higher oxygen content in biodiesel, which facilitates complete combustion.

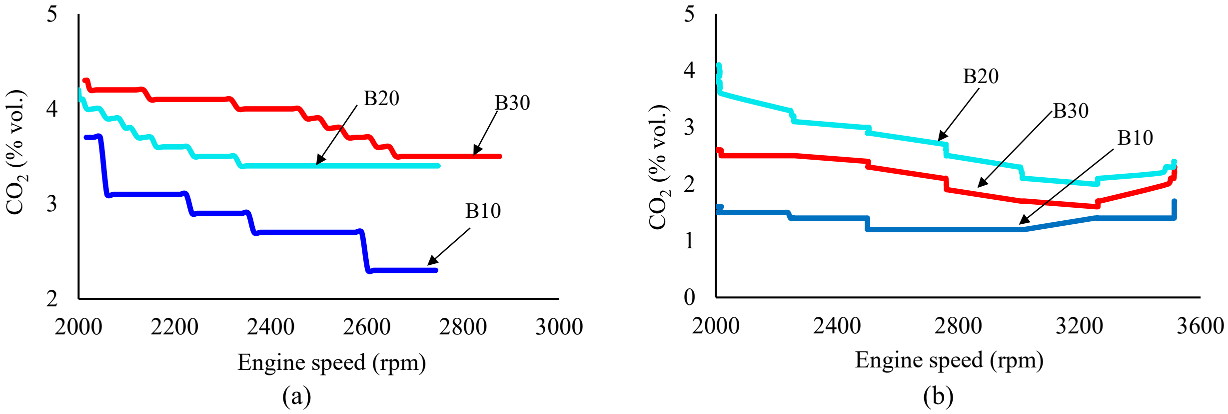

Figure 8. CO_2 emission for all tested fuels using (a) sweep test and (b) step test.

Figure 9 shows a comparison of the CO emissions for all the tested fuels for both the sweep test and step test. B10 has the lowest CO emission in both tests compared to B20 and B30, with B20 having the highest emissions. It is also noted from the graph that increasing speed in the step test resulted in a gradual reduction of CO emissions for B20 and B30.

It should be noted that carbon monoxides measured during the test do not correlate with the expected results available in the literature, where carbon monoxides decreased with increasing blending ratio. The contrary results could be attributed to a number of factors; the differences in ambient conditions during experiments, since experiments for each blend were carried on different days. However, specific investigations need to be conducted to establish factors that would contribute to such an unexpected outcome.

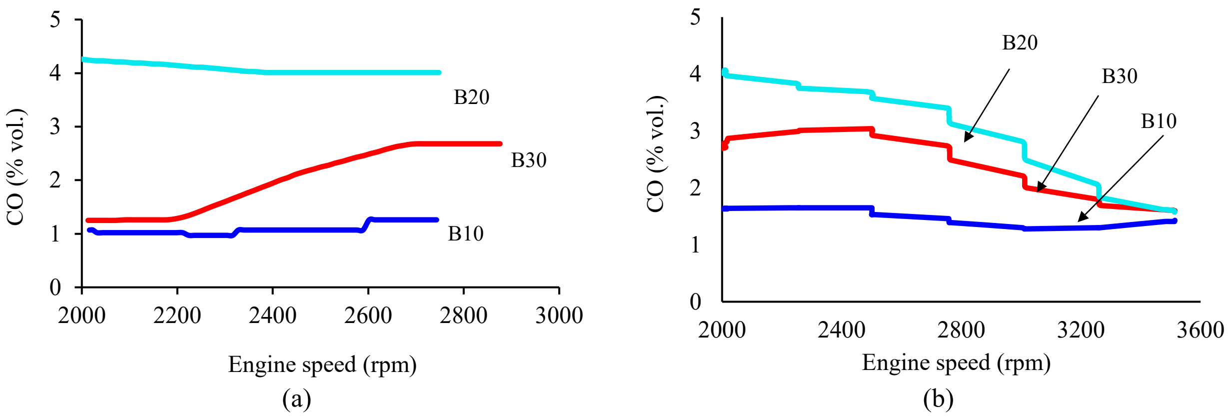

Figure 9. CO emission for all tested fuels using (a) sweep test and (b) step test.

The results from Figure 10 show that NO_x emission decrease with an increase in blending ratio. During both sweep and step test, the results show that B30 had the lowest NO_x emissions, second by B20, with B10 having the highest NO_x emission. A reduction in NO_x emission with the increase in biodiesel blend ratio might be due to the increased viscosity with the increase in blend ratio. The higher viscosity causes an increase in the length of molecules, subsequently suppressing molecules of nitrogen from reacting with molecules of oxygen existing in biodiesel, causing less NO_x formation with the increase in blending ratio.

For both the sweep test and the step test, Figure 11 indicates a difference in hydrocarbon emissions. It is found that B10 had the lowest HC emission values in both tests, followed by B30 and B20 emitting the highest hydrocarbon values. However, the HC emission values decline with an increase in engine speed for the step test. The expected results were to observe a decrease in HC emission with an increase in biodiesel blend. The contrary findings might be attributed to the differences of environmental conditions as the experiments were carried out on different days

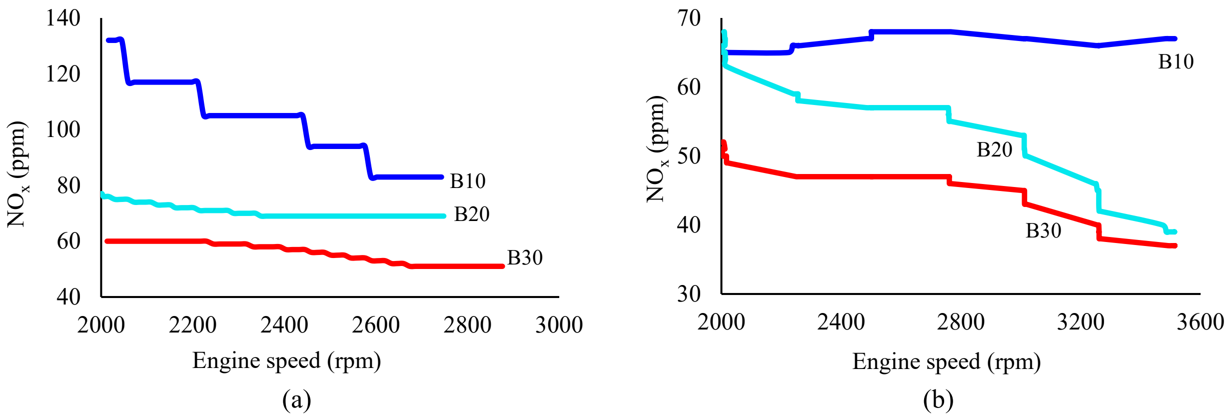

Figure 10. NO_x emission for all tested fuels using (a) sweep test and (b) step test.

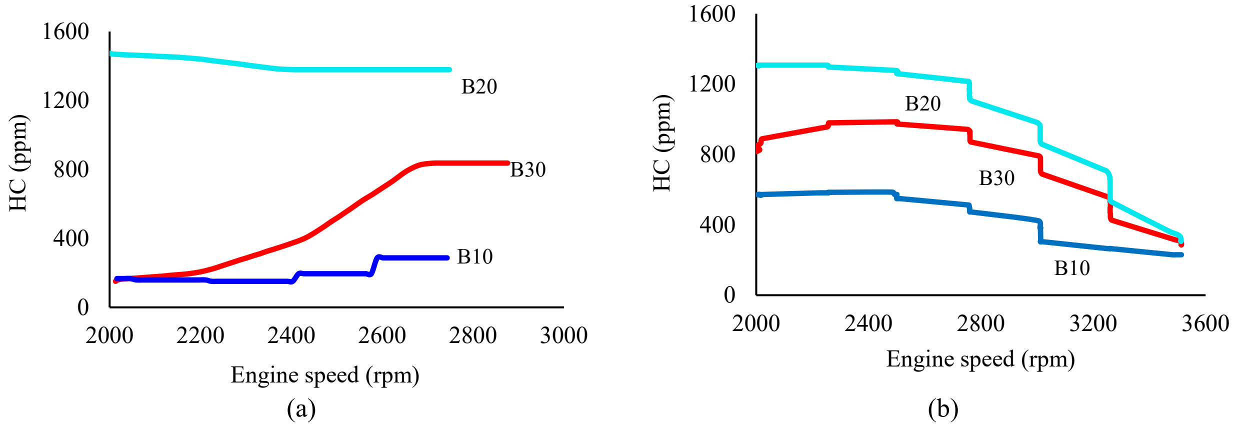

Figure 11. HC emission for all tested fuels using (a) sweep test and (b) step test.

Figure 12 shows that B30 has the worst fuel consumption among the three fuel blends and that fuel consumption is improving as the percentage of biodiesel decreases, with B10 having the best fuel consumption. This was expected as the fuel's energy content decreases as the percentage of biodiesel in fuel increases.

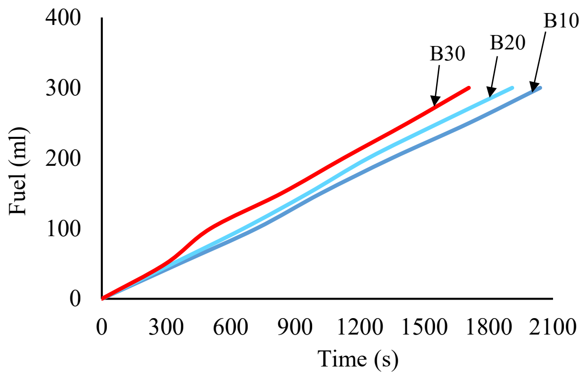

Figure 12. Fuel consumption variation.

CONCLUSION

The results from this study reveal that both coefficient of friction and wear scar diameter increase with the increase of biodiesel percentage. Therefore, it can be concluded that any degree of engine oil dilution by biodiesel reduces the performance of engine oils. The engine performance with biodiesel blends is not linear with the blending, however on average, B30 demonstrated better performance of both torque and power output in both sweep test and step test compared to B10 and B20. On the other hand, B30 demonstrated poor performance in terms of fuel consumption, where the experiment results showed that fuel consumption increased with an increase in biodiesel percentage.

Based on the outcome of this study, palm oil biodiesel blends can be employed as a potential alternative fuel for diesel engines owing to improved combustion and performance characteristics of CO_2, torque and power with an increase in blend ratio. However, there is a need to investigate further specific factors that contributed to contrary increased CO and HC emissions with the increase of blending ratio.

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