Effects of Various Alcohol Blends on Performance and Emissions of Small Compression Ignition Engine Fuelled with Diesel-20% Palm Oil Methyl Ester

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Abstract. As a promising option of in improving alternative fuels, alcohol such as butanol, methanol, and ethanol can be used in diesel engine. However, there is lack of detailed investigation of the effects of variation addition of butanol, methanol, and ethanol with diesel-palm oil methyl ester (B20) on engine performance and emissions release. This study represents to fully evaluate the potential impact of addition butanol, methanol, and ethanol blended with B20 on engine performance and emissions released by single cylinder compression ignition (CI) engine at engine speeds of 2700, 3100, and 3500 rpm under load of 50%. The results of engine performance and emissions of 10ml ethanol, methanol and, butanol each blended with B20 are compared. Experimental results showed that the B20 + 10ml methanol has an advantage over diesel-biodiesel blend in Brake Specific Fuel Consumption (BSFC) which reduces about 10.42% at every different engine speed. Besides, the B20 + 10ml methanol has reduced the emission of Nitrogen Oxide, Carbon Monoxide, Carbon Dioxide, and Hydrocarbon by 27.84%, 14.28%, 5.19%, and 56.25%. In overall, the addition of 10ml methanol on B20 blend shows the most significance result for the engine performance and emissions at all test condition.

Keywords: fuel, compression ignition, emissions, engine performance

1. Introduction
Extensive use of diesel fuel for transportation all over the world has caused its supplies to continuously decrease and has aggravated environmental pollution. Therefore, the high demand of diesel fuel has stimulated many researchers to investigate alternative fuels such as diesel -biodiesel blend to overcome the crisis. Biodiesel is one of the alternative ways to replace current fuel source that has a good potential to perform up to fill in the demands in case of fuel depletion. Biodiesel can effectively reduce engine-out emissions, particularly unburned HC, CO, and NOx in a typical four-stroke compression-ignition engine. This is crucial in developing an innovative way to substitute or even better, upgrade the current fuel market to be greener without sacrificing performance too much. Higher oxygen content in biodiesel will increase the overall complete combustion in the engine hence higher value of Brake Thermal Efficiency (BTE). This will also help to ensure lower Brake Specific Fuel Consumption (BSFC) which is ideal in finding an alternative fuel [1-6].
A study by Bueno et al. [7] states that both soybean and castor biodiesel increase the CO emissions caused by the biodiesel iodine value. Castor bean or castor oil plant is one of the promising non-edible oil crops since it has low implementation and production costs and relative resistance to hydric stress. However, the result of the study shows that castor oil biodiesel blending into diesel fuel did not advance fuel injection for the engine in use and continuously increased the NOx emissions. Other authors concluded that the effect of biodiesel on NOx emissions depends on the type of engine and its operating conditions. It will be easier to analyse the engine performance results by increasing the biodiesel ratio in the blended fuel because the measurement and evaluation of blended fuel property is an important indicator [8]. An effort to improve popular B20, Asiah et al. [9] investigated the effect of various Tripmexx additive mixed into 80% diesel and 20% biodiesel (B20) with an amount of 0.1 ml (B20-0.1), 0.2ml (B20-0.2), and 0.3ml (B20-0.3) compared to conventional pure diesel. As a result, B20-0.3 gives the best brake specific fuel consumption (BSFC) and higher brake thermal efficiency (BTE) while lower carbon monoxide (CO) and hydrocarbon (HC). Fuel additive is chemical that are used to enhance the properties of the fuel. Currently, numerous chemical additives are used in transportation to improve the quality of biodiesel fuel and diesel fuel in order to convene up the most wanted performance level [10]. Additives may help petroleum to recover its engine combustion, performance, and emission environmental standards. Various studies have proven that adding additives in biodiesel enhancing engine performance and reduce engine emissions.

As a promising option of in improving alternative fuels, alcohol such as butanol, methanol, and ethanol can be used in combustion whether gasoline or diesel [11, 12]. Butanol is produced from through chemical processes based on oxo synthesis, Reppe synthesis, or crotonaldehyde hydrogenation [13]. While methanol is made from coal and natural gas but it can also made from renewable sources, such as wood and papers while ethanol is produced a from the renewable sources that come from fermentation of carbohydrate containing biomass like sugar, grains and tapioca [14, 15]. These trio alcohols may give benefit that could save the environment from pollution by decreasing the toxic emission such as carbon dioxide, carbon monoxide, hydrocarbon, and nitrogen dioxide.

In order to make effect comparison between trio alcohol which blended in 80% diesel blended with 20% palm oil methyl ester (B20), this study is carried out. Thus, experiment of alcohols such as butanol, ethanol, and ethanol blended with B20 on the performance and emissions of a small compression ignition engine. From here, the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) of the alcohols blended with B20 biodiesel. Finally, the emission of nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO2) from the combustion may be compared.

2. Experimental Setup

The experiment is started with sample preparation of various types of B20 blended with different but same volume.

2.1. Samples Preparation

Sample of biodiesel fuel blends were prepared through mechanical mixing and blending (based on volume). Briefly, each biodiesel blends are added with constant 10ml alcohol additives. 100% diesel (D100) will be a baseline reference for this research to compare later. The test fuels were B20 + 10ml Methanol, B20 + 10ml Ethanol, and B20 + 10ml Butanol. Each of the mixture was stirred continuously for 30 minutes by using an electric magnetic stirrer and left for 30 minutes to reach an equilibrium at room temperature before they were subjected to any test as recommended by previous research [16]. Sample property tests were carried out to compare different value of Calorific Value (CV), viscosity, and density. The results were differentiated in graphs.
2.2. Engine Test
The experiments are conducted in Automotive Engines Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM) Shah Alam. A single cylinder CI engine is used to carry out the experiment as shown in Figure 1. The engine with a specification in Table 1 is operated at different speed of 2700, 3100, and 3500 rpm with load at 50%. The engine speeds are measured using a digital tachometer. Three types of alcohol with 10ml volume are blended with 20% blends of palm oil methyl ester biodiesel (B20) which are the butanol (Bu10), methanol (M10), and ethanol (E10) are fuelled into the engine.

![Figure 1. Schematic diagram of the experimental setup.](image)

The engine had been running approximately for ten minutes with diesel fuel after the test then the fuel was changed for the next test to ensure the accuracy and the consistency of the measurement data. Furthermore, the engine fuel tests were repeated three times for each fuel at the specified test conditions in order to have a reliable measurement. Exhaust emissions data was by using a MRU Infrared Gas Analyzer to detect output of CO, CO\textsubscript{2}, HC, and NO\textsubscript{x}. The gas analyser has been calibrated by the company to assure the accuracy of the data collection.

| Engine Type        | Single-cylinder, 4-stroke air-cooled diesel engine |
|--------------------|--------------------------------------------------|
| Fuel Tank Capacity [L] | 1.5                                              |
| No. of Cylinder     | 1                                                |
| Displacement [cc]   | 418                                              |
| Bore x Stroke [mm]  | 70x57                                             |
| Displacement ([L]   | 0.219                                             |
| Compression Ratio   | 8.5                                               |
| Max Power [hp/rpm]  | 10/3600                                           |
| Rated Power [kW]    | 4.5                                               |
| Lubrication         | Oil SAE10W/30                                     |
3. Results and Discussion

Engine performance parameter such as Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) are calculated, and the data of exhaust emission such as CO, NOx, CO\(_2\), and HC are justified.

3.1 Properties of Fuel Blends

Figure 2 shows the result comparison between of viscosity for tested fuels (D100, B20, B20 + M10, B20 + E10, B20 + Bu10). Kinematic Viscosity is the ratio of dynamic viscosity to the density of fluid. The results are arranged in the order B20 (0.00494 Pa.s), B20 + Bu10 (0.00434 Pa.s), B20+M10 (0.00416 Pa.s), B20 + E10 (0.00409 Pa.s) and D100 (0.00334 Pa.s). It is stated that B20 has the highest kinematic viscosity compared to other tested fuels. Fuels with high viscosity tend to form larger droplets in the injection resulting in poor fuel atomization, which increases the penetration of the spray tip and decreases the angle of the spray, resulting in poor combustion. This ultimately also increase the exhaust emission engine [17, 18].

However, by adding the alcohol blend with biodiesel, the results seem to be compensated where kinematic viscosity decreases as seen from the result B20 + Bu10 (0.00434 Pa.s), B20 + M10 (0.00416 Pa.s), B20 + E10 (0.00409 Pa.s). Lower viscosity is one of a good consideration for diesel engine in reducing friction losses; hence better fuel consumption [19, 20]. In summary, the percentage of reduction blended fuels compared to B20 is B20 + Bu10 (12.15%), B20 + M10 (15.79%), and B20 + E10 (17.29%). In conclusion, B20 + E10 (0.00409 Pa.s) provides a kinematic viscosity closer to diesel, which makes it more compatible with injection systems used in most of diesel engines. Calorific Value (CV) for D100, B20, B20+M10, B20+E10 and B20 + Bu10 is shown in Figure 3. CV or known as heating value is defined as heat released by the fuel when it is completely burnt and measured at constant volume or constant pressure and the hot gas is cooled back to its initial temperature [21, 22]. It can be classified into low heating value (LHV) and high heating value (HHV). Based on the graph, CVs are obtained as D100 (4.4496), B20 (3.9515), B20 + E10 (3.9266), B20 + M10 (3.8502), and B20 + Bu10 (3.5655). It is proven that the addition of alcohol in biodiesel blend gives a significant lower CV compared to diesel [12]. In summary the percentage reduction of CV for blended fuels when compared with B20 is B20 + E10 (0.63%), B20 + M10 (2.56%), and B20 + Bu10 (9.77%).

![Figure 2. Viscosity of tested fuel](image-url)
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Figure 3. Calorific value of tested fuel.

Figure 4 shows the pattern value of density for all tested fuel (for D100, B20, B20 + M10, B20 + E10, and B20 + Bu10). Density is a mass of fuel per unit volume. The density plays an important role in determining the performances and emissions in internal combustion engine. One important property of diesel fuel is its physical properties such as density [23]. Based on the value shown on bar graph Figure 4, the highest density obtained by B20 + E10 with 1109 kg/m$^3$ while the lowest density value is obtained by D100 with 922 kg/m$^3$. If a fuel has higher density than other, it means much more mass is entering into the combustion chamber for the same volume, since new generation diesel injectors which supply fuel into combustion chamber for power generation regulate the amount of fuel by volume, not by mass. Much more fuel entering combustion chamber means an increase of emissions [24]. In conclusion, the sequence of density value for tested fuels is D100 (922kg/m$^3$), B20 + Bu10 (923kg/m$^3$), B20 + M10 (950kg/m$^3$), B20 (958kg/m$^3$) and B20 + E10 (1109kg/m$^3$). While the percentage of reduction blended fuels when compared with B20 is B20 + M10 (0.84%) and B20 + Bu10 (3.65%) but increment in B20 + E10 (13.62%).

3.2 Engine Performance

3.2.1 Brake specific fuel consumption

Figure 5 demonstrate regarding brake specific fuel consumption (BSFC) of all tested full (D100, B20, B20 + M10, B20 + E10 and B20 + Bu10) at different engine speed (2700, 3100, and 3500 RPM) while at constant load (50%). BSFC is known as the relation between mass fuel consumption and brake power. It can be seen from the result that B20 (165, 180 and 210 g/kW.h) blend has the highest value of BSFC as compared to D100 (135, 150 and 170 g/kW.hr) at different engine speed (2700 rpm, 3100 rpm and 3500 rpm). In brief, 18.1% of percentage different is the highest where the BSFC produce by B20 blend.
is 165 g/kW.h and D100 is 135 g/kW.h at 2700 rpm. The rate of BSFC in B20 blend increase due to the lower calorific value of B20 compared to the D100 [17]. In this case, diesel engine needs to consume more B20 blend to develop the same power as diesel origin.

![Figure 5. BSFC vs different Engine Speed with constant load](image)

Nevertheless, it could also be seen from the result that BSFC decrease compared to B20 when B20 blend are fuelled with alcohol-diesel blend (M10, E10 and Bu10) at the same volume (10%). The BSFC that produced at 2700 RPM engine speed shows the lowest pattern among three engine speeds as for the example the lowest BSFC for blended fuel is B20 + Bu10, and it is the nearest to diesel origin. It means that the blend of B20 + Bu10 has shown the highest reduction (15.15%) in BSFC when compared to the blend of B20 at constant load of 50%. This concludes the blend of B20 + Bu10 has better BSFC than B20, B20 + M10 and B20 + E10. This case is due to the presence of Bu10 in the blend fuel of B20. The benefit of the presence of Bu10 is butanol has high cetane number, low vapour pressure, and lower miscibility making it more suitable diesel fuel additive than ethanol and methanol [18]. Other than that, butanol has good properties as substitute for ethanol, with higher energy content in addition to enhance mixing properties and has lower autoignition temperature than methanol and ethanol as well [19]. In conclusion the sequence for reduction of BSFC compared to B20 is B20 + E10 (3.03%), B20 + M10 (9.09%) and B20 + Bu10 (15.5%).

### 3.2.2 Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) results are shown in Figure 6 for diesel fuel and blends of B20, B20 + M10, B20 + E10, and B20 + Bu10. BTE defines the ability of the combustion to accept experimental fuel and offers comparable means of determining how effectively the fuel energy has been converted into mechanical performance. The graph displays the result of BTE for all tested fuels decreasing from low engine speed (2700 rpm) to the highest engine speed (3500 rpm). It may because of the combustion temperature is low, therefore incomplete combustion takes place; on the other hand, at the highest engine speed, the combustion temperature is high and the fuel/air ratio is richer, however there is not enough time for mixing of fuel and air, resulting incomplete combustion and decrease in BTE. It also states the highest BTE among three engine speed is at the lowest engine speed (2700 rpm) where D100 (16.2%), B20 (14.3%), B20 + M10 (17.0%), B20 + E10 (14.0%), and B20 + Bu10 (16.7%) at 50% engine load. Other than that, it can be observed that diesel fuel has the higher BTE compared to B20 blend. It may because of the different number of carbon where D100 contains more carbon atom in longer chains than B20 [20]. Besides, D100 has higher fuel temperature compared to B20 thus increase the BTE value [21].
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The BTE for blend B20 + M10 at 3 engine speed (2700 rpm, 3100 rpm and 3500 rpm) is the highest (17.0%, 16.0%, and 13.3%) compared to other blend fuels even diesel origin. The increasement of BTE for B20 + M10 is (9.72%) from three different engine speed compared to diesel origin. This is could be attributed to the presence of methanol in B20 blend where methanol has the shortest chain and the lowest molecular weight among all the tested alcohols which leads to easier ignition and better combustion and hence resulting highest BTE [17]. In addition, the lowest boiling point of methanol among the tested alcohols causes reduction in heat losses and hence resulting in higher BTE.

In conclusion, the blends for B20 and B20 + E10 experience reduction at three engine speed where is B20 (8.76%) and B20 + E10 (1.66%) while B20 + M10 and B20 + Bu10 experience increase at three engine speed where is B20 + M10 (9.72%) and B20 + Bu10 (5.38%).

3.2.3 Exhaust Emission

Figure 7 shows the behaviour of concentration carbon monoxide (CO) at different engine speed for tested fuel of D100, B20, B20 + M10, B20 + E10, and B20 + Bu10. All tested fuels are decrease in brake specific carbon monoxide (BSCO) when the engine speed increases. The graph also depicts that all tested blended fuels cause BSCO increase at low engine speed (2700 rpm) compared to diesel fuel. The reason is because at lowest engine speed (2700 rpm) the effect of lower combustion temperature where cooling effect due to higher latent heat of evaporation, dominates the effect of oxygen content of the blended fuel as complete combustion, which suppress the CO oxidation process, resulting in the increase in BSCO emission compared to diesel [18,19]. From the average for three engine speeds, the reduction in BSCO emissions using all alternative fuels are in sequencing B20 + M10 (14.28%), B20 + Bu10 (6.25%), B20 (2.97%), and B20 + E10 (0.14%) comparison with diesel. This results also prove that other studies also obtained reduction in B20 and B20 + Bu10 [25].

However, when the engine speed increase, the effect of combustion temperature becomes lesser and it can be seen at highest engine speed (3500 rpm) which BSCO emissions of all the blended fuels are lower than diesel fuel. From the result, B20+M10 has the highest influence reduction of BSCO (14.28%) that can be attributed to the long duration of combustion, and hence longer time for oxidation of CO to CO₂ [26].
Figure 7. BSCO Vs Engine Speed with constant load.

Figure 8 shows the variation of the brake specific Hydrocarbon (BSHC) of different fuel blends with respect to variation engine speed at constant load (50%). Based on the graph, BSHC for all tested fuels decrease by increase the engine speed. At low engine speed (2700 rpm), BSHC emissions for all tested fuel are high due to the insufficient combustion temperatures to initiate complete combustion. However, at higher engine speed the combustion temperatures are high enough to achieve more complete combustion, leading to decrease in BSHC for all tested fuels. The results from the graph also depicts all the blended fuels (irrespective of B20 + E10 at 2700 RPM) could reduce the BSHC from low engine speed (2700 rpm) to the highest engine speed (3500 rpm).

The consequence of incomplete combustion contributes to higher latent heat of evaporations of alcohols and biodiesel compared to net diesel is the factor of increments BSHC at low engine speed (2700 rpm). Nevertheless, it is found that BSHC emission for blended fuels is lower than net diesel at high engine speed (3500 rpm) due to the dominant factor of higher oxygen content of the blended fuels that cause more complete combustion and increase the oxidation of unburned hydrocarbons at higher in-cylinder temperatures [27]. There are also proven by some studies that found a rise in THC at low engine speed and reduction at high engine speed with the use of alcohol diesel blends compared to diesel [28, 29]. In addition, other studies also found that the use of B20 + E10 and diesel blended with ethanol or methanol could increase the combustion quality due to more oxygen content in the fuel, and reduce the THC, in comparison with diesel fuel [30-33].

On the average for three engine speeds, the reduction of BSHC are in the order of B20 + M10 (56.25%), B20 (9.38%), B20 + E10 (2.5%), and B20 + Bu10 (1.4%) compared to diesel. From the results, it can be concluded that the effect of using B20 + M10 on reduction of BSHC (56.25%) is higher than other blended fuels which is due to the better combustion.

Figure 9 shows the results for brake specific Nitrogen oxides (BSNOx) emissions with the use of D100, B20, B20 + M10, B20 + E10, and B20 + Bu10. The graph display that the BSNOx emissions approximately decrease with rise in engine speed (RPM). Besides, it also reveals that all the blended fuels (except B20 at all engine speed) causes decrease in BSNOx at all the tested loads compared to
diesel fuel. From the results, it can be concluded that on the average reduction for three engine speed, reduction in BSNOx with use of blended fuels are in the order B20 + M10 (27.84%), B20 + E10 (10.79%), B20 + Bu10 (5.81%) while B20 has increasing (6.7%) in BSNOx compared to diesel.

In spite of, the huge effect of combustion temperature on formation of NOx can be revealed from the results that length of combustion duration (residence time) also has effect on NOx formation. This is due to the blend of B20 + M10 which has highest decrement of BSNOx (27.84%) among all the tested blended fuels due to the shortest duration of combustion. Meanwhile, the increment of B20 (6.7%) in BSNOx is due to the highest duration combustion.

There are studies found that increase in alcohol branch cause reduction in NOx emission due to the increasing in ignition delay and decrease in adiabatic flame temperature [34]. In addition, there are also studies regarding reduction of BSNOx using ethanol [28, 35] and butanol [36]. It can be concluded from the above result that the effects of higher latent heat of evaporation and lower heating value of alcohol fuels are dominant factors compared to other parameters (such as lower cetane number and higher oxygen content of blends which increase the combustion temperature) that cause reduction in BSNOx for different engine speed.

The behaviour of BSCO2 emissions that fuelled with D100, B20, B20 + M10, B20 + E10 and B20 + Bu10 at three different engine speeds for could be seen in Figure 10. From the results, it is observed that the highest BSCO2 emission is recorded at 2700 rpm engine speed while the lowest BSCO2 emissions is recorded at 3500 rpm. It concludes that higher engine speed cause reduction in BSCO2 due to the more complete combustion.

On the other hand, the graph also shows that all the blended fuels (except B20) could reduce BSCO2 emissions compared to diesel. This is also proven from the studies that reported there are reduction of BSCO2 with ethanol and B20 + E10 [24, 28, 37] and a slight increase in BSCO2 using pure biodiesel.
The reason behind the reduction of BSCO₂ in blended fuels compared to diesel is due to the lower carbon-to-hydrogen ratio and the higher oxygen content of the blended fuel [24, 33].

The percentage of reduction in BSCO₂ are in the order B20 + M10 (5.19%), B20 + Bu10 (2.42%), and B20 + E10 (0.69%), while increment of BSCO₂ emissions in B20 (5.86%) with comparison of diesel. It can be deduced that only B20 + M10 is effective on reducing BSCO₂ with reduction of 5.86% among all the blended fuels compared to diesel.

4. Conclusions
From the experiment, B20 has a higher BSFC and lower BTE for engine performances. Oppositely, B20 also shows a disadvantage on exhaust emission where increment of CO, HC, NOx, and CO₂ emission showed up. When the alcohol (butanol, methanol, and ethanol) with 10ml are fuelled into alcohol-diesel-biodiesel blend, the performance characteristics (BSFC, BTE) and emission characteristics show a better result compared to non-alcohol biodiesel. In overall, the addition of 10ml methanol in B20 shows the most significance result for the engine performance and emissions at all test condition.

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