Performance and Emission Measurement of a Single Cylinder Diesel Engine Fueled with Palm Oil Biodiesel Fuel Blends

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Abstract. A high concentration of palm oil biodiesel fuel blend is a strong candidate to substitute conventional diesel fuel (B10) due to its prospect to release fewer emissions. This paper shall present findings when testing palm oil biodiesel fuel blends (B10, B20, and B30) at medium speed (2500 rpm) in a single-cylinder Yanmar L70N diesel engine coupled to an eddy current dynamometer. In this study, a timed burette and an airbox determined the engine's fuel and air consumption, respectively. In contrast, a flue gas analyzer measured the emission released by the fuel blend. The result indicates that as the concentration of palm oil biodiesel increases in the blends (from B10 to B30), there is no significant difference (average less than 5%) between the fuel blends in terms of brake thermal efficiency, brake specific fuel consumption, and air-fuel ratio. On the other hand, the emission results showed a reduction in CO, CO₂, and NOₓ when the concentration of palm oil biodiesel increases in the blends. Considering the fuel blend would have no significant difference in the engine performance and its ability to reduce most emission, it is safe to conclude that B30 would be a good alternative for current diesel fuel (B10).

1. Introduction
The automotive industry is popularly accused of why climate change is still an unresolved issue. Many are aware – even preschoolers – that vehicles’ emission causes global sufferings such as prolonged drought, sudden flooding, crop failure, and many more. While there have been policies introduced and new technologies deployed to combat it, it is evident that the world needs more, and we are indeed in a race to patch the world before it is too late.

Although many are now concentrating on electric vehicles, EVs, this technology is still a few years away to fully replace vehicles operating by internal combustion engines. EVs still rely on power plants that mainly consume crude oil to power the EVs, and there are still debates on safer ways to dispose of retiring batteries. Contrary, EVs may still damage the environment instead of being its savior. Even when these issues were resolved, massive transports on the sea and even lighter transports on developing countries' roads may still rely on petroleum fuel and the much familiar internal combustion engines.

Since the world may need to cope with internal combustion engines painting the road for a few more years, an immediate solution with smaller changes is necessary to resolve this emission problem. An obvious solution would be to either modify the vehicle or improve what it consumes. The former might
be developing a more efficient manufacturing process, improving engine combustion quality, or marketing sustainable vehicles. In contrast, the latter could be the application of biodiesel fuel blends on compressed ignition diesel engines.

Biodiesel fuel blend is a binary mixture of diesel and biodiesel at predetermined concentrations. The application of biodiesel fuel blend for diesel engines is not entirely new that many countries had already begun switching to it. Globally, biodiesel fuel blends exist in varying feedstocks – due to countries' having different resources and economic aspects [1] – and concentration. Furthermore, there are different generations of biodiesels: edible oils, non-edible oils, and waste oils, as the successor solved issues of its predecessor [2]. In recent years, biodiesel fuel blends are no longer binary. There are now tertiary and quaternary blends with either alcohol or vegetable oil mixed with the initial diesel and biodiesel component [3].

From here, there is a need to qualitatively determine and compare the performance of a biodiesel fuel blend with another. The reason is to determine the optimum fuel blend within the broad range of possible feedstocks, components, and concentrations and determine its suitability in an actual engine. Numerous biodiesel fuel blends had blended throughout the years, and researchers rigorously tested them in engines of all shapes and sizes. There were works to compare the performance between biodiesel fuel blends of similar feedstock but with different concentrations, such as performed by Gad et al. [4] and vice versa, as performed by Abed et al. [5]. Another example was comparing different generations of biodiesels' performance as performed by Yesilyurt et al. [3].

Biodiesel fuel blends are named based on the concentration of biodiesel components in the blend. Here, a B30 palm oil biodiesel fuel blend means a blend consisting of 30% palm oil biodiesel and 70% diesel fuel. With the difference in concentration, the fuel blends' properties vary, especially its density, viscosity, calorific value, and cetane number. When quantifying the performance of biodiesel fuel blends, researchers agree that it depends on these four properties. Comparatively, diesel tends to have a lower density, viscosity, and cetane number but has higher calorific value compared to palm oil biodiesel fuel blends.

The Malaysian Palm Oil Board, MPOB, oversees the nation palm oil asset and produces palm oil biodiesel. Along with the Malaysian Government, they are hoping to mandate a higher percentage of palm oil biodiesel fuel blend (B20) and replaces the already commercialized B10. Previously, there had been researching works centering on B20. However, as the year progressed, there had been improvements in the blends’ manufacturing process, thus possibly improving its quality and rendering previous results obsolete. Due to this, there is a need to reinvestigate its performance in the engine and emission aspect. Hence, this paper shall present findings in these aspects when testing three blends of palm oil biodiesel fuel blends at different concentrations, namely: B10, B20, and B30 in a single-cylinder Yanmar L70N diesel engine.

2. Methodology

2.1. Fuel Properties and Handling

In this paper, three palm oil biodiesel fuel blends were supplied by MPOB with B10 serving as the reference blend. This reference follows B10 as already a commercialized fuel in Malaysia, and the following tests compare the remaining two fuel blends against B10. The fuel blends are binary blends, consisting of only diesel and biodiesel components, and are absent of any other additives. Table 1 lists the properties of the fuel blends, determined using respective ASTM standards. Due to the fuel blends hygroscopic and auto-oxidation nature, the fuel blends were stored in 20 liters oil containers and were
under a regulated temperature to avoid fuel degradation. Other than this, operators were made sure to wear latex gloves and thoroughly flush the engine when testing the next fuel blend. This meticulous handling ensured that there is no impurity in the blends, and their quality is maintained.

2.2. Test Procedures

The three biodiesel fuel blends were tested on a diesel engine with the specification shown in Table 2. Figure 1 shows the schematic diagram of the test rig. From here, the diesel engine was coupled to a 130-kW eddy current Magtrol brake dynamometer to control and maintain the engine speed. The fuel blends were tested at five different loads and at a fixed speed of 2500 rpm, the engine average operating speed. Before the experiment, the atmospheric conditions were first recorded, namely: the atmospheric pressure, temperature, and humidity. Experiments were postponed if the current atmospheric conditions are too different from previous conditions. Data were collected when the engine reached a steady-state condition and is an average of three data under the same operating condition.

The engine was connected to an airbox with a 77-mm diameter orifice and a digital manometer. The water level height in the manometer was used to determine the air consumption rate using Equation 1. Aside from this, a modified burette was installed between the engine and the fuel reservoir. By using the burette and a stopwatch, the fuel consumption was determined. With the air consumption rate and the fuel consumption rate, the Air Fuel Ratio was later determined. Aside from this, the brake specific fuel consumption and the brake thermal efficiency were calculated using equation 2 and equation 3.

Next, to quantify the emission performance, a Testo 350 gas analyzer was used to sample the exhaust gas. The gas analyzer was installed with a CO, CO2, and NOx emission sensor to measure exhaust gas emissions. The gas analyzer's probe was placed inside the exhaust tailpipe, and an operator began sampling the gas by initializing the analyzer software. This software was installed on a personal computer.

| Table 1. Properties of Tested Fuel Blends |
|-----------------------------------------|
| Tested Fuel | Density (kg/m³ @ 40°C) | Kinematic Viscosity (mm²/s @ 40°C) | Calorific Value (kJ/kg) | Cetane Number |
| B10 | 855.4 | 4.610 | 45,634 | 54.4 |
| B20 | 855.0 | 4.524 | 44,964 | 57.8 |
| B30 | 861.2 | 4.595 | 44,409 | 59.0 |

| Table 2. Engine Specification |
|------------------------------|
| Displacement | 320 Cubic Centimeters |
| Compression ratio | 20:1 |
| No of Cylinder (Bore x Stroke) | Vertical single cylinder (78 mm x 67 mm) |
| Max Power | 4.9 kW / 3600 rpm |
| Max Torque | 18 Nm / 2400 rpm |

\[
m_a = 64.94C_d d^2 \sqrt{\frac{h p_a}{T_a}} \tag{1}
\]
\[ BSFC = \frac{m_f}{P_b} \]  
\[ \eta_c = \frac{P_b}{m_f Q_{CV}} \]  

3. Results and Discussion

3.1. Engine Performance

The brake thermal efficiency implies the percentage of chemical energy from the fuel blends converted to mechanical energy. Figure 2 shows that as the load increases and is approaching maximum the brake thermal efficiency increases. This is due to the extra heat generated at high load. Figure 2 also shows that as the concentration of palm oil biodiesel increases in the blends, the thermal efficiency decreases as agreed by Singh et al. [6]. They argued that the decreasing efficiency is due to the fuel blends decreasing calorific value (heat produced in complete combustion) as the biodiesel concentration in the blends increases. The result agrees with this statement since the calorific value of tested fuel blends does decrease with increasing palm oil biodiesel in the fuel blends. B10 having the highest calorific value generated the highest thermal efficiency whereas B30 having the lowest calorific value generated the lowest thermal efficiency. On the other hand, Teoh et al. [7] suggested that rich oxygen molecule promotes complete combustion, thus improving the brake thermal efficiency. This reason could be why B30 – which contains richer oxygen molecule than B20 – overtook B20 at mid load operation.
Figure 2: Brake Thermal Efficiency of Palm Oil Biodiesel Fuel Blends

Figure 3 shows the brake specific fuel consumption, BSFC of palm oil biodiesel fuel blends. The figure shows that as the load increases, the brake specific fuel consumption decreases. Figure 3 also shows that the brake specific fuel consumption increases as the biodiesel concentration increases in the blend. A higher concentration of biodiesel fuel blends has a lower caloric value, which results in an increase in BSFC. Engines using these fuel blends would therefore consume more fuel to maintain the load. This generally means for a fixed volume of the biodiesel fuel blends, engines fueled with B10 would travel further than engines fueled with B30. Referring to equation 2, BSFC is directly proportional to the fuel consumption rate.

Figure 3: Brake Specific Fuel Consumption of Palm Oil Biodiesel Fuel Blends

The Air Fuel Ratio is the ratio of air and fuel consumption. A diesel engine is commonly operated under a lean condition where more air is consumed than fuel. Figure 4 shows that the engine did operate in a lean condition, and the AFR decreases with increasing engine load. The figure also shows that B10 has the highest AFR, while B30 is the lowest. B30 has high oxygen content, which further reduces the AFR since the engine requires fewer external air for the combustion process. This shows that a higher concentration of biodiesel fuel blends helps to promote better combustion as compared to neat biodiesel fuel blends.
From these figures, it is evident that the blends' performance differences are not significant with each other. Table 3 shows the percentage difference of the different fuel blends with B10 as the reference fuel. The percentage difference is at most 7.67%. This small percentage difference denotes that if an engine switches fuel blends, the performance difference would not be too noticeable. The results obtained could apply to multi-cylinder engines under a similar test condition.

**Table 3: Engine Performance Percentage Difference Against B10**

| Torque (Nm) | B20 Air Fuel Ratio (%) | B20 Brake Specific Fuel Consumption (%) | B20 Thermal Efficiency (%) | B30 Air Fuel Ratio (%) | B30 Brake Specific Fuel Consumption (%) | B30 Thermal Efficiency (%) |
|-------------|------------------------|-----------------------------------------|-----------------------------|------------------------|-----------------------------------------|-----------------------------|
| 2.1         | -1.18                  | 2.48                                    | -0.97                       | -5.59                  | 5.85                                    | -2.92                       |
| 4.2         | -0.64                  | 2.98                                    | -1.45                       | -4.61                  | 5.00                                    | -2.14                       |
| 6.3         | -5.33                  | 7.67                                    | -5.74                       | -6.05                  | 6.67                                    | -3.67                       |
| 8.4         | -4.32                  | 3.29                                    | -4.33                       | -6.49                  | 3.90                                    | -2.87                       |
| 9.0         | 2.34                   | 0.63                                    | -0.24                       | 2.19                   | 6.06                                    | -4.17                       |

3.2. Emission Performance

Figure 5 shows an increase in the percentage of carbon monoxide, CO released with the increased engine load. However, with the increasing concentration of palm oil biodiesel, fewer CO were released, similar to Saravanan et al. [8]. The formation of CO is due to incomplete combustion [7]. The results showed that a higher blend of biodiesel helps to reduce CO. In times, Saravanan et al. [8] suggested that extra oxygen molecules might react and generate carbon dioxide, CO₂. Like Figure 5, the percentage of CO₂ in Figure 6 increases with an increasing load but decreases with the increase in palm oil biodiesel concentration. Anwar et al. [9] implied that the increase in CO₂ emission is due to the fuel blends' high oxygen content and its high cetane number. This result agrees with Anwar et al. [9] since B30 has the highest cetane number of 59.0 and generates the fewest CO₂ at all loads. The CO and CO₂ content agree with the oxygen, O₂ content released by the palm oil biodiesel fuel blends. From Figure 7, at high load, the O₂ content is low. Referring to Figure 5 and Figure 6, it is observed that the CO and CO2 content is high at high load. Since the total number of oxygen molecules is fixed, fewer O₂ molecules were generated since more oxygen molecules generated CO and CO₂.
Figure 5: Carbon Monoxide, CO Content of Palm Oil Biodiesel

Figure 6: Carbon Dioxide, CO₂ Content of Palm Oil Biodiesel

Figure 7: Oxygen, O₂ Content of Palm Oil Biodiesel
For nitrogen oxides in Figure 8, the emission released increases with the increased engine load but decreases with the increasing concentration of palm oil biodiesel. Contrary to common findings, the result showed that a higher concentration of biodiesel fuel blend produces fewer NO\textsubscript{x} compared to a lower concentration of biodiesel fuel blends. The formation of NO\textsubscript{x} is directly dependent upon the inside temperature of the combustion chamber [10]. Shrivastava et al. [10] implied that a higher concentration of biodiesel fuel blend might have a lower combustion temperature, which is ascertained by the lower exhaust gas temperature. Since the formation of NO\textsubscript{x} depends on the temperature phenomenon, the lower combustion temperature causes fewer generation of NO\textsubscript{x}.

From these figures, it is evident that B30 generated the fewest emission. From Table 4, B30 at the highest load produces 9.11% fewer carbon monoxide, 12.25% fewer carbon dioxide, and 28.10% fewer oxides of nitrogen compared to the baseline fuel B10. At low load, a similar reduction trend is also observed. At mid load operation, the percentage difference is not uniform due to the inconsistent heat generated in the engine which affects the generation of emission.

| Torque (Nm) | CO (%) | CO\textsubscript{2} (%) | NO\textsubscript{x} (%) | CO (%) | CO\textsubscript{2} (%) | NO\textsubscript{x} (%) |
|-------------|--------|-----------------|-----------------|--------|-----------------|-----------------|
| 2.1         | -9.19  | -6.54           | -9.92           | -24.34 | -12.85          | -16.33          |
| 4.2         | -6.52  | -3.89           | -10.79          | -19.12 | -8.83           | -17.09          |
| 6.3         | -2.84  | -6.10           | -1.54           | -10.14 | -9.15           | -10.21          |
| 8.4         | -5.57  | -9.99           | -9.04           | -0.49  | -11.51          | -22.37          |
| 9.0         | -3.28  | -6.07           | -8.75           | -9.11  | -12.25          | -28.10          |

### Table 4: Emission Performance Percentage Difference Against B10

4. **Conclusion**

This paper determined the performance and measured the emission released by three palm oil biodiesel fuel blends from MPOB. Malaysia had mandated the usage of B10 for diesel engines and is currently mandating B20 to replace B10. Based on the results, the following conclusions were made.

- B30 is an acceptable successor to replace B20 in the future.
• The performance difference of B30 is not significant against B10 and B20. The percentage differences for air-fuel ratio, brake specific fuel consumption and thermal efficiency is an average less than 5%.
• The brake specific fuel consumption of B30 is slightly higher than B20 and B10.
• However, B30 compensates with the significant reduction of CO, CO₂, and NOₓ compared to B20 and B30.

Indeed, mandating B30 for diesel engines would effectively reduce the national greenhouse gas released. When comparing the tested palm oil biodiesel fuel blends and its previous version, the tested fuel blends' quality had improved. This paper recommends further identifying and investigating the decisive factors that improved the quality of the fuel blends. This paper also recommends testing the fuel blends at different conditions and proving the fuel blend's lower combustion temperature due to the decreasing trend of nitrogen oxide emitted as the concentration of palm oil biodiesel increases in the fuel blend.

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