Evaluation of a novel biofuel from unwanted waste and its impact on engine performance, emissions, and combustion characteristics in a diesel engine

Y. H. Teoh, *a-c H. H. Masjuki, a I. M. Noor, *b B. Si Ali, b M. A. Kalam a and H. G. Hwa a

The effect of a new biofuel source derived from waste palm oil mill effluent (POME) addition to diesel on engine performance, emissions, and combustion characteristics was investigated in a single-cylinder diesel engine under six different speed operations and at full load conditions. The experimental results suggested that there are some penalties in engine torque, brake power, brake specific fuel consumption (BSFC), and brake specific nitrogen oxide (BSNOx) with the presence of Biopro Diesel™ fuel in the blend. Moreover, there is an improvement in exhaust emissions with lower brake specific hydrocarbons (BSHC), brake specific carbon monoxide (BSCO) and smoke emissions by using Biopro Diesel™ fuel blends across all engine speeds. Besides, the tip surfaces of the injectors running with Biopro Diesel™ blends were found to be cleaner than that of an injector running with fossil diesel. Moreover, there is an improvement in the combustion process with a shorter total burning angle for Biopro Diesel™ fuel blends than that of diesel at all engine speeds. Overall, the results suggested that biofuel derived from waste POME blended with fossil diesel can be used satisfactorily in an unmodified diesel engine.

1. Introduction

The current global fossil fuel crisis and environmental pollution issues have triggered investigations on new alternative fuel sources. Biofuel is considered an alternative fuel because of its biodegradability, renewability, non-toxicity, having no aromatic hydrocarbons, and carbon neutrality.¹ ² Biofuel, especially biodiesel, is defined as monoalkyl esters of fatty acids synthesised from renewable vegetable oil, animal fats, and waste cooking oil, which emits fewer harmful emissions than petroleum diesel.³ Currently, about 95% of the global biodiesel is derived from edible oils such as rapeseed (84%), sunflower oil (13%), palm oil (1%), soybean oil and others (2%).⁴ However, the extensive use of edible crops for fuel purposes has brought about great concerns recently.⁵ Serious human starvation issues, especially in developing countries, may arise due to utilising much of the available arable land area. From an environmental perspective, serious ecological imbalances caused by deforestation for plantation purposes may cause damage to wildlife. Therefore, biofuel produced from a non-edible or waste source has gained much more attention than ever before.

In Malaysia, the palm oil industry has served as an important backbone to the country’s overall economy, providing both employment and income from exports.⁶ It was reported that in year 2008 the total export of palm oil and its derived products all together was worth RM 64 808 million (USD 20 268 million), or 9.8% of the total national revenue.⁷ At the same time, the palm oil industry also generates a large quantity of waste whose disposal is a challenging task.⁸ In a typical palm oil plantation, about 70% of the fresh fruit bunches are turned into waste in the form of empty fruit bunches, fibres and shells, as well as liquid effluent. With the recent technological advancement, these by-products’ waste can be converted to other value-added products or energy to generate additional profit for the palm oil industry. In recent years, the Biopro Diesel™ biofuel produced by Gyrus Tech Sdn Bhd, a University of Malaya spin-off company, has been an example of the value-added products produced from the waste POME. This biofuel is derived by converting waste POME using bioprocess technology, with the process having been perfected by Dr Ishenny and his team from the Department of Chemical Engineering, University of Malaya.

Biofuel recovery from waste POME is a new approach in managing biomass waste for promoting sustainability of the palm oil industry.

Biopro Diesel™ fuel is an attractive alternative to fossil diesel fuel for many applications in which commercial diesel is used, such as transportation, industry application, electrical power generators, etc. It is safe, clean and economically competitive compared to fossil diesel. In year 2012, it was reported that the production cost of Biopro Diesel™ was USD
0.50 per litre, which was about 10 cents cheaper than the fossil diesel price at that time. In terms of marketability, the introduction of Biopro Diesel™ fuel is definitely profitable to the palm oil industry, since their generated waste can now be turned into wealth.

The main objective of the present paper is to investigate the feasibility of operating Biopro Diesel™ in a single-cylinder light-duty diesel engine without modification, and compare the engine performance (engine torque, brake power, and BSFC), emissions (BSNOₓ, BSCO, BSHC, and smoke), and combustion characteristics (cylinder pressure, heat release rate, and total burning angle) to those of baseline diesel. Two blends of Biopro Diesel™—diesel blends (10% and 25%) were prepared and tested. The engine test was conducted at full load with varying speeds (1400–2400 rpm with 200 rpm increments). Lastly, it is notable that this study proposes a novel, alternative biofuel feedstock as a source of energy in a compression ignition engine.

2. Methodology

2.1. Materials

The simplified process flow diagram to produce Biopro Diesel™ from fresh fruit bunches of palm oil is shown in Fig. 1. In Malaysia, the most typical way to extract palm oil from fresh fruit bunches is through a wet palm oil milling process. This process involves various stages in which a huge amount of steam and water is required for sterilising and washing. As a result, a significant amount of wastewater is produced from a palm oil mill and this wastewater is known as POME. Biopro Diesel™ is a new invention resulting from the conversion of waste POME into biofuel by using a bioprocess approach. Biopro Diesel™ provides an excellent alternative in handling POME and produces highly valuable products from unwanted waste. Biopro Diesel™ fuel was invented by Dr Ishenny Mohd Noor et al. with the related plant model, technology used, and processes having been patented via the University of Malaya (UM Patent no: PI 2011700182). The Biopro Diesel™ fuel used in the present study was supplied by and obtained from Gyrus Tech Sdn Bhd, a University of Malaya spin-off company.

2.2. Fuel properties test and analysis

In this paper, a total of three types of fuel, including diesel (as baseline fuel), BP10 (90% diesel + 10% Biopro Diesel™ on a volume basis) and BP25 (75% diesel + 25% Biopro Diesel™ on a volume basis) were tested. Table 1 shows the key physicochemical properties of diesel, diesel–Biopro Diesel™ blends and neat Biopro Diesel™ in comparison with ASTM and EN biodiesel standards. The table also includes with a summary of the equipment and methods used to determine the fuel properties. Apparently, all of the physicochemical properties of neat Biopro Diesel™ are satisfied with the ASTM and EN biodiesel standards, except for being marginally higher in viscosity than the EN standard. Generally, biodiesel can be operated in a diesel engine either in its pure form or blended with petroleum diesel. Lower-level blends of 10% and 25% are considered in this study, mainly because they represent a good balance in terms of engine performance, emissions, production cost, cold-weather performance, and materials compatibility. In fact, lower-level blends generally do not require engine modifications. As shown in the Fig. 2 is the fuel colour comparison for the fuels used in the present study.

The key physicochemical properties of Biopro Diesel™ in comparison with market-available diesel, Euro 2M and Euro 4M standards as tabulated in Table 1. The Euro 2M and Euro 4M standards were proposed by Malaysia’s Department of Environment under the Ministry of Natural Resources and Environment. The latter was introduced to the market in 2009 and the former is expected to be implemented in 2015. Apparently, both of the standards are localised Malaysian versions of the Euro 2 and Euro 4 specifications. Some degree of modification needs to be done on the Euro specifications to suit the Malaysian climate, temperature and environments. In the present study, the Biopro Diesel™ fuel was produced and benchmarked with Malaysia’s Euro 2M and Euro 4M diesel standards. It is commonly agreed that the fuel injection system in a diesel engine is very sensitive to the kinematic viscosity of fuel. An Engine operating on high-viscosity fuel will cause poor fuel atomisation and combustion inefficiency. From the result it can be seen that the viscosity of Biopro Diesel™ fuel had fallen within the Euro 2M and Euro 4M diesel standards. Also, other key fuel properties such as pour point, flash point, total acid number, cetane number, and total sulfur content of Biopro Diesel™ fuel were found to be better than Euro 2M and Euro 4M diesel standards. This implies that the Biopro Diesel™ fuel is suitable for use as a transportation fuel.

2.3. Engine setup and instrumentation

The experimental work was carried out with a single-cylinder, direct-injection diesel engine. The SAJ SE-20 model 20 kW eddy current dynamometer was used to provide loading to the engine and to maintain engine speed. The intake airflow was measured using a Bosch air mass sensor. In addition, a Kobold fuel flow meter was employed to measure the fuel consumption of the engine. Temperature values of ambient air, exhaust gas, lubricant oil, and cooling water were measured using K-type thermocouples. The specifications of the test engine are given.

![Fig. 1 Biopro Diesel™ processing flow diagram.](Image)
in Table 2. The experiment setup arrangement is shown in Fig. 3.

The test system was equipped with the necessary sensors for combustion and fuel injection timing analysis. In-cylinder gas pressure was measured using a Kistler 6125B type pressure sensor. To mount the sensor in the engine head through a water-cooling jacket, a dedicated mounting sleeve was fabricated and installed. The charge signal output of the pressure sensor was converted to a low impedance voltage signal by a PCB model 422E53 in-line charge converter, and this unit was powered by a PCB model 480E09 signal conditioner. To acquire the top dead center (TDC) position and crank angle signal for every engine rotation, a high-precision incremental encoder with 720 pulses per revolution was used. To determine the start of injection (SOI) timing, the fuel line injection pressure was measured with a PCB 108A02 type dynamic pressure sensor, and its signal was conditioned with a PCB 480E09 type signal conditioner. To simultaneously sample the cylinder pressure, injector pressure signal, and encoder signals, a computer equipped with a high-speed ADLINK DAQ-2010 simultaneous sampling data acquisition card, which has 14 bits resolution, 2 MS per s sampling rate, and four analogue input channels, was used. The acquired data were further processed and analysed with Matlab software. To reduce noise effects, Savitzky–Golay smoothing filtering was applied to the sampled cylinder pressure data.

### Table 2 Engine specification

<table>
<thead>
<tr>
<th>Engine model</th>
<th>Single cylinder, water cooled 4-stroke DI diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>92 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>96 mm</td>
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<tr>
<td>Displacement</td>
<td>638 cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.7 : 1</td>
</tr>
<tr>
<td>Continuous rating output</td>
<td>10.5 hp @ 2400 rpm</td>
</tr>
<tr>
<td>1-Hour rating output</td>
<td>12.0 hp @ 2400 rpm</td>
</tr>
<tr>
<td>Injection timing</td>
<td>17° BTDC</td>
</tr>
</tbody>
</table>
Combustion parameters, such as peak pressure magnitude, peak pressure location, heat release rate, peak heat release rate location, and total burning angle, were all computed using Matlab software.

For exhaust emission measurement, an AVL DICOM 4000 5-gas analyser was used to measure the concentration of CO, HC, and NO\textsubscript{x}. Opacity for smoke measurement was measured with AVL DiSmoke 4000. All emissions were measured during steady-state engine operation. The measurement range and resolution of both of the instruments are given in Table 3.

For enhanced accuracy, each test point was repeated three times to yield the average readings in performance and exhaust emissions. The experiments were conducted under full load conditions. The engine speed was varied from 1400 to 2400 rpm with increments of 200 rpm. For injector nozzle carbon deposition analysis, the nozzle tip was dismantled from the injector and replaced with a new one at the end of the testing of each fuel. Thus, a total of three nozzle tips were collected for visual inspection.

### 2.4 Uncertainty analysis

In every experimental work, errors and uncertainties can arise from instrument selection, condition, calibration, environment, observation, reading, and test procedure. The measurement range, accuracy and percentage uncertainties associated with the instruments used in this experiment are listed in Table 4. Uncertainty analysis is necessary to verify the accuracy of the experiments. Percentage uncertainties of various parameters such as brake power (BP), brake specific fuel consumption (BSFC), brake specific nitrogen oxide (BSNO\textsubscript{x}), brake specific carbon monoxide (BSCO), brake specific hydrocarbon (BSHC), and smoke were determined using the percentage uncertainties of various instruments employed in the experiment. To compute the overall percentage uncertainty due to the

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Measurement principle</th>
<th>Component</th>
<th>Range</th>
<th>Resolution</th>
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</thead>
<tbody>
<tr>
<td>Gas analyzer</td>
<td>NDIR</td>
<td>Carbon monoxide (CO)</td>
<td>0–10% vol</td>
<td>0.01% vol</td>
</tr>
<tr>
<td></td>
<td>NDIR</td>
<td>Unburned hydrocarbon (HC)</td>
<td>0–20 000 ppm vol</td>
<td>1 ppm</td>
</tr>
<tr>
<td></td>
<td>Electrochemical</td>
<td>Nitrogen oxides (NO\textsubscript{x})</td>
<td>0–5000 ppm vol</td>
<td>1 ppm</td>
</tr>
<tr>
<td>Smoke opacimeter</td>
<td>Photodiode detector</td>
<td>Opacity (%)</td>
<td>0–100%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

Fig. 3 Schematic diagram of experimental setup.
Table 4 List of measurement accuracy and percentage uncertainties

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Measurement range</th>
<th>Accuracy</th>
<th>Measurement techniques</th>
<th>% Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>±80 Nm</td>
<td>±0.1 Nm</td>
<td>Strain gauge type load cell</td>
<td>±0.25</td>
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<tr>
<td>Speed</td>
<td>0–10 000 rpm</td>
<td>±1 rpm</td>
<td>Magnetic pick up type</td>
<td>±0.1</td>
</tr>
<tr>
<td>Time</td>
<td>—</td>
<td>±0.1 s</td>
<td>—</td>
<td>±0.2</td>
</tr>
<tr>
<td>Fuel flow measurement</td>
<td>0.5–36 L h⁻¹</td>
<td>±0.1 L h⁻¹</td>
<td>Positive displacement gear wheel flow meter</td>
<td>±0.2</td>
</tr>
<tr>
<td>Air flow measurement</td>
<td>2–70 L s⁻¹</td>
<td>±0.04 L s⁻¹</td>
<td>Turbine flow meter</td>
<td>±0.5</td>
</tr>
<tr>
<td>CO</td>
<td>0–10% by vol</td>
<td>±0.001% vol</td>
<td>Non-dispersive infrared</td>
<td>±1</td>
</tr>
<tr>
<td>HC</td>
<td>0–20 000 ppm</td>
<td>±1 ppm</td>
<td>Non-dispersive infrared</td>
<td>±1</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0–5000 ppm</td>
<td>±1 ppm</td>
<td>Electrochemical</td>
<td>±0.44</td>
</tr>
<tr>
<td>Smoke</td>
<td>0–100%</td>
<td>±0.1%</td>
<td>Photodiode detector</td>
<td>±1</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>0–25 000 kPa</td>
<td>±10 kPa</td>
<td>Piezoelectric crystal type</td>
<td>±0.5</td>
</tr>
<tr>
<td>Crank angle encoder</td>
<td>0–12 000 rpm</td>
<td>±0.125°</td>
<td>Incremental optical encoder</td>
<td>±0.03</td>
</tr>
</tbody>
</table>

Computational

| Brake power       | —                  | ±0.04 kW | —                               | ±0.1         |
| BSHC              | —                 | ±2.7 g kW⁻¹ h⁻¹ | —                           | ±1           |
| BSNOₓ             | —                 | ±0.01 g kW⁻¹ h⁻¹ | —                         | ±0.9         |
| BSFC              | —                 | ±0.1 g kW⁻¹ h⁻¹ | —                           | ±2.5         |

Combined effect of the uncertainties of various variables, the principle of propagation of errors is considered and can be estimated as ±3.25%. The overall experimental uncertainty was computed as follows:

Overall experimental uncertainty = square root of 

\[ \sqrt{(uncertainty \ of \ fuel \ flow \ rate)^2 + (uncertainty \ of \ BP)^2 + (uncertainty \ of \ BSFC)^2 + (uncertainty \ of \ BSNO_x)^2 + (uncertainty \ of \ BSFC)^2 + (uncertainty \ of \ smoke)^2 + (uncertainty \ of \ pressure \ sensor)^2 + (uncertainty \ of \ crank \ angle \ encoder)^2} = \] 

\[ \sqrt{[(0.2)^2 + (0.1)^2 + (1.1)^2 + (2.5)^2 + (0.9)^2 + (1)^2 + (1)^2 + (0.5)^2 + (0.03)^2]} = \pm 3.25\% \]

3. Calculations

3.1. Engine performance

The engine performance in this work is evaluated based on brake power and BSFC. These parameters can be determined according to the following equations:

\[ \text{Brake power (kW)} = \text{Torque} \times \text{Speed} \] \((1)\)

\[ \text{BSFC (g kW}^{-1} \text{ h}^{-1}) = \frac{\text{Fuel consumption}}{\text{Brake power}} \] \((2)\)

3.2. Combustion analysis

Heat release rate (HRR) analysis is a useful approach for assessing the effects of a fuel injection system, fuel type, engine design changes, and engine operating conditions on the combustion process and engine performance.\(^{11}\) Given the plot of HRR versus crank angle, it is easy to identify the start of combustion (SOC timing), the fraction of fuel burned in the premixed mode, and differences in combustion rates of fuels.\(^{12}\) In the present paper, fuels with different blend ratios are fuelled in the identical compression ignition engine; thus, the HRR information is an important parameter in interpreting engine performance and exhaust emissions. In this study, the averaged in-cylinder pressure data of 100 successive cycles, acquired with a 0.125° crank angle resolution, was used to compute the HRR. The HRR, given by \(\frac{dQ_{\text{th}}}{d\theta}\), at each crank angle was obtained from the first law of thermodynamics, and it can be calculated by the following formula:

\[ \frac{dQ_{\text{th}}}{d\theta} = \frac{\gamma}{\gamma - 1} \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \frac{V}{\partial P/\partial \theta} \] \((3)\)

where \(\gamma\) = specific heat ratio, \(dQ_{\text{ht}}/d\theta\) = heat transfer to the chamber walls (J/°C), \(P\) = instantaneous cylinder pressure (Pa), and \(V\) = instantaneous cylinder volume (m³).

4. Results and discussions

4.1. Engine performance

4.1.1. Engine torque. The engine torque variations with engine speed for various fuel blends under full load conditions is illustrated in Fig. 4. It is shown that the peak torque occurred at an engine speed of 1400 rpm for all fuels. Essentially, the brake torque of Biopro Diesel™ blends shows a similar trend to that fuelled with baseline diesel. Besides, it can be observed that the diesel fuel produced higher torque than other blended fuels across all engine speeds. In fact, the BP25 fuel blend at 2400 rpm shows the largest drop in torque with the variation of 10.9% with respect to the baseline diesel fuel. This can be related to their combined effect of relatively lower heating value and slightly higher kinematic viscosity than diesel fuel (see Table 1).\(^{13}\)

4.1.2. Brake power. The engine brake power variations with engine speed for various Biopro Diesel™ blends under full load conditions is shown in Fig. 5. The results suggested that the peak power occurred at an engine speed of 2200 rpm for all fuels. Besides, it can be seen that the brake power of Biopro
Diesel™ fuel blends reveals a similar trend to that fuelled with baseline diesel. Across the entire speed range, it can be observed that the diesel fuel produced higher power than other fuels. In fact, the BP25 fuel blend at 2400 rpm shows the largest drop in power with the variation of 10.93% with respect to the baseline diesel fuel. The variation in power for all fuel blends with respect to baseline diesel can be seen in Fig. 6.

4.1.3. Brake specific fuel consumption (BSFC). Engine performance and fuel consumption were strongly governed by the physical and chemical properties of the fuel used. To assess the engine performance with different fuel blends, a useful performance indicator, namely brake specific fuel consumption (BSFC) was used. BSFC is defined as the ratio of the fuel consumption rate to the brake power output. The BSFC versus engine speed for various Biopro Diesel™ fuel blends in comparison with baseline diesel is shown in Fig. 7. From the results it can be seen that BSFC for all fuel blends is higher than baseline diesel across the speed range. Essentially, the BSFC of all Biopro Diesel™ blends shows a similar trend to that fuelled with baseline diesel. In fact, the BP25 fuel blend at 1800 rpm shows the largest BSFC variation of 7.8% with respect to baseline diesel fuel. This can be related to their relatively lower heating value of 6% than baseline diesel fuel (see Table 1); thus, more fuel is needed to attain the same amount of torque.

4.2. Exhaust emissions

4.2.1. Brake specific nitrogen oxides (BSNOₓ). The variation of BSNOₓ emissions with engine speed for the Biopro Diesel™ blends and diesel is shown in Fig. 8. In the present study, the consistent behaviour of the variation of BSNOₓ can be observed with the use of Biopro Diesel™ in the blend across the speed range. Generally, the BSNOₓ emissions are minimum at a mid-engine speed of around 1800 and 2000 rpm, and higher at lower and higher ends of the engine operating speed. It can be seen that, in general, however, the BSNOₓ for all of the Biopro Diesel™ fuel blends is higher than for baseline diesel across the speed range. It can be seen that the BSNOₓ increases with the higher Biopro Diesel™ in the blend across the speed range. In fact, there is an apparent average increment of 15% (BP10) and 37.1% (BP25) in BSNOₓ from the baseline case across all engine speeds. This can be associated with the intrinsic oxygen content in the Biopro Diesel™ samples and, thus, provide additional oxygen for the formation of BSNOₓ. Another possible reason can be associated with the reduction in the heat dissipation by radiation, as a consequence of the large reductions of soot emitted with the use of Biopro Diesel™, thus increasing the BSNOₓ emissions.

4.2.2. Brake specific carbon monoxide (BSCO). During combustion, CO is predominantly formed when the available oxygen is insufficient to oxidise all of the carbon in the fuel to carbon dioxide. Fig. 9 shows the variation of BSCO emissions with engine speed for the Biopro Diesel™ blends and baseline diesel. The general trend indicates that the BSCO emissions are minimum at a mid-engine speed of around 1800 to 2000 rpm, and higher at lower and higher ends of the engine operating speed for all tested fuels. Besides, it can be seen that the BSCO reduction benefit of Biopro Diesel™ in the blend is maintained at all engine speeds. Moreover, the increases of Biopro Diesel™ concentration in the blend also tend to reduce the BSCO emissions at all engine speeds. There is an apparent average reduction of 35.1% (BP25) and 9.7% (BP10) in BSCO emissions from the baseline case. This can be attributed to the increasing

![Fig. 4 Engine torque versus engine speed for the tested fuels.](image)

![Fig. 5 Engine power versus engine speed for the tested fuels.](image)

![Fig. 6 Variation in changes of power with engine speed for the tested fuels.](image)
oxygen content in Biopro Diesel™ fuels being used, which promotes cleaner and better combustion efficiency.  

4.2.3. Brake specific hydrocarbon (BSHC). As seen in Fig. 10, the effect of Biopro Diesel™ addition in the fuel blends on BSHC emissions can be clearly observed. The introduction of Biopro Diesel™ improves the combustion process and reduces the BSHC emissions across all engine speeds. This also suggests that adding oxygenated fuels can partially mitigate hydrocarbon formation via locally over rich mixture. It was also observed that the maximum reduction of BSHC emissions is 28% for BP25 at 1600 rpm compared with the baseline diesel.

4.2.4. Smoke. Smoke is an unwanted by-product of combustion in compression ignition engines, which is primarily formed through incomplete combustion of hydrocarbon fuel. Generally, the smoke from the exhaust tailpipe is emitted visibly in the form of dark, black smoke. The composition of the smoke strongly depends on the type of fuel and engine operating condition. In this study, the variation in smoke opacity with Biopro Diesel™ blends is shown in Fig. 11. The magnitudes were found to be relatively lower with all the Biopro Diesel™ blends. It was observed that the maximum reduction is 36.9% with BP25 at 1800 rpm compared with baseline diesel. Combined effects of higher oxygen and lower sulfur content of Biopro Diesel™ fuel are believed to be responsible for the decrease in the smoke opacity level.  

4.3. Injector deposit analysis

As shown in Fig. 12, injector deposit accumulation appeared during visual inspection for all fuel samples. Besides, tip surfaces of the injectors running with Biopro Diesel™ blends were found to be cleaner and less carbon built up than that of an injector running with baseline diesel. Note that the photographs of each injector nozzle with each fuel type (i.e. (b) to (d)) were taken after nearly 2 hours of engine operation under full load conditions. The accumulated 2 hours of engine operation under full load conditions. The injector nozzle was replaced with a new nozzle during each fuel change to eliminate any surface deposition from the previous run.

4.4. Combustion characteristics

4.4.1. Cylinder combustion pressure. The comparison of in-cylinder combustion pressure for all of the tested fuels at various engine speeds under full load conditions is shown in
Fig. 13a–c represent variation of in-cylinder combustion pressure at 1400 rpm, 2000 rpm, and 2400 rpm, respectively. It can be seen that the in-cylinder peak pressure decreased with the increase in Biopro Diesel™ concentration in the blends for all engine speeds. At 1400 rpm, slight decreases in peak cylinder pressure can be seen for the Biopro Diesel™-blended fuels compared to the baseline diesel. The maximum peak cylinder pressure was found to be 82.7 bar at 7.875° ATDC with the baseline diesel, while the minimum peak cylinder pressure was found to be 81.5 bar at 7.75° ATDC with the BP25 fuel blend. As the engine speed increased to 2000 rpm, it was observed that the maximum peak cylinder pressure was established to be 69 bar at 9° ATDC with the baseline diesel, and the lowest peak cylinder pressure was found to be 67 bar at 8.875° ATDC with the BP25 fuel blend. At 2400 rpm, the baseline diesel recorded the highest peak cylinder pressure, which was 59.6 bar at 7.625° ATDC and the lowest peak cylinder pressure was 57.3 bar at 7.5° ATDC with the BP25 fuel blend. Generally, it is clear that with the higher Biopro Diesel™ blend ratio, the peak cylinder pressure decreases as a consequence of relatively lower calorific value of Biopro Diesel™ than diesel.

4.4.2. Heat release rate. The heat release rate (HRR) for different fuels at various engine speeds and at full load conditions is shown in Fig. 14. For all Biopro Diesel™ blends, it is observed that the peak HRR which happened during the premixed combustion phase is consistently lower than that of baseline diesel at all engine speeds. In fact, prominent reduction in the peak HRR can be observed with a higher Biopro Diesel™ fraction in the blend. Again, this may be related to the lower calorific value of the Biopro Diesel™-blended fuels than diesel. Another possible reason can be due to the relatively higher viscosity of Biopro Diesel™-blended fuels, hence causing slow vaporisation of Biopro Diesel™ which contributes less premixed combustion. The largest reduction of peak heat release of BP25 was found to be 40.5%, 4.8% and 7% lower than baseline diesel at 1400 rpm, 2000 rpm and 2400 rpm, respectively. Another useful parameter to evaluate from the heat release rate analysis is the combustion duration. The total burning angle in this study is defined as the period between
10% and 90% mass burnt. In Fig. 15, it is observed that on average the total burning angles for Biopro Diesel™-blended fuels are 0.5°/CA and 1.5°/CA for BP10 and BP25, respectively, shorter than that of diesel at all engine speeds. The same observation was also reported by An et al. that shorter combustion duration was observed for Biopro Diesel™. The shorter combustion duration of Biopro Diesel™ means it has a faster burn rate than baseline diesel, especially during the diffusive combustion phase. This is postulated to the faster chemical reaction and oxygenated fuel structure of Biopro Diesel™, hence shortening the mixing time required for diffusive burning.

5. Conclusion

In the present study, an engine was successfully operated with biofuel derived from waste POME. Two potential blends of Biopro Diesel™-diesel (BP10 and BP25) were prepared and tested. The results of performance and emissions were compared with baseline diesel. The following main conclusions can be drawn from the present study.

The brake torque and brake power for all of the Biopro Diesel™ fuel blends were lower than those of baseline diesel across the speed range. The BP25 fuel blend at 2400 rpm shows the largest drop in torque with the variation of 10.9% with respect to the baseline diesel fuel.

There are some penalties in BSNOx emissions with the presence of Biopro Diesel™ fuel in the blend. Moreover, there is an improvement in exhaust emissions with lower BSCO, BSHC, and smoke emissions by using Biopro Diesel™ fuel blends across all engine speeds. The largest smoke reduction of 36.9% was observed with BP25 at 1800 rpm compared with baseline diesel.

From the visual inspection, the tip surfaces of the injectors running with Biopro Diesel™ blends were found to be cleaner than that of an injector running with fossil diesel.

For the combustion characteristics it can be observed that there are some decreases in peak combustion pressure and peak HRR as a consequence of relatively lower calorific value of Biopro Diesel™ blends than diesel. On the other hand, there is an improvement in the combustion process with a shorter total burning angle for Biopro Diesel™-blended fuels than that of diesel at all engine speeds.

From this overview it can be concluded that Biopro Diesel™ fuel is a viable alternative fuel source. Biopro Diesel™ blends can be operated satisfactorily in an unmodified diesel engine. However, more research and development on durability testing, material compatibility, and detailed field assessment need to be performed prior to the extensive utilisation in a diesel engine.

Nomenclature

ASTM American Society for Testing and Materials
ATDC After top dead centre
Acknowledgements

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