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Willyanto Anggono; Gabriel J. Gotama; Kevin Jonathan; Fandi D. Suprianto; Teng Sutrisno

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Fuel Properties and Diesel Engine Performances of Biodiesel Blends derived from *Salacca zalacca* Seed Oil

Willyanto Anggono[1, 2, a)], Gabriel J. Gotama[1, 2, b)], Kevin Jonathan[1, 2, c)], Fandi D. Suprianto[1, 2, d)], and Teng Sutrisno[1, 2, e)]

[1]*Mechanical Engineering Department, Petra Christian University*
Jl. Siwalankerto 121-131, Surabaya 60236, Indonesia
[2]*Centre for Sustainable Energy Studies, Petra Christian University*
Jl. Siwalankerto 121-131, Surabaya 60236, Indonesia

[a)] Corresponding author: willy@petra.ac.id
[b)] m24413007@alumni.petra.ac.id, [c)] m24413010@john.petra.ac.id, [d)] fandi@petra.ac.id, [e)] tengsutrisno@petra.ac.id

Abstract. Biodiesel has been proposed as an alternative renewable fuel to reduce the dependency on fossil fuels. Since the quality of the biodiesel blends depends on the feedstock and the biodiesel-to-diesel ratio, an extensive study on a specific biodiesel feedstock should be conducted. Despite the abundance of *Salacca zalacca* plants in Southeast Asia, there is a lack of studies regarding their potential as biodiesel feedstock. Therefore, this study investigated the fuel properties and the diesel engine performances of biodiesel derived from *Salacca zalacca* seed oil. The biodiesel blends investigated have a biodiesel-to-diesel ratio of 10:90 (B10) and 20:80 (B20). Studies of the fuel property found that the flash point, distillation temperature at 90% recovery, and the Sulphur content of B10 and B20 need improvement to adhere to the biodiesel standards. The results from the engine performance studies under engine speeds of 1800 to 3000 RPM suggest that the performances of B10 are comparable to that of conventional diesel fuel. However, B10 falls short on its brake specific fuel consumption and thermal efficiency under low engine speed. Future works will focus on improving the fuel properties and engine performances of B10 to allow biodiesel derived from *Salacca zalacca* seed oil as a fossil fuel substitute.

INTRODUCTION

Most of the energy produced today is derived from combusting fossil fuels. The overreliance on fossil fuel to produce energy is not sustainable as it has limited reserves [1, 2]. Furthermore, the by-products of combusting fossil fuels include greenhouse gases, such as CO2 (carbon dioxide), which intensify climate change and damage the environment [3, 4]. Solutions have been proposed to circumvent the overutilization of fossil fuel, including optimizing the engine setup [5, 6, 7, 8] and substituting fossil fuel with biofuel [9, 10].

Biodiesel is a biofuel that is promising as a substitute for fossil fuel. Studies have highlighted the advantages of using biodiesel fuel. Biodiesel can be produced from renewable feedstocks and wastes [11,12,13], which help to sustainably produce energy and clean the environment. Generally, biodiesel has lower CO (carbon monoxide), HC (hydrocarbon), and PM (particulate matter) emissions compared to the conventional diesel fuel [14,15, 16, 17]. Studies on other gas products such as NOx (nitrogen oxides) and CO2 have mixed results; some suggest that biodiesel may have similar or lower emission levels compared to the diesel fuel [14, 15, 16, 18]. In terms of engine performances, studies have suggested that biodiesel may improve the BMEP (brake mean effective pressure) [11], fuel consumption [19, 20], and BTE (brake thermal efficiency) [20] when compared to diesel fuel.

Although there are advantages in replacing fossil fuel with biodiesel, the fuel properties and engine performances of biodiesel are dependent on the type and quality of the feedstock [21] and the biodiesel-to-diesel ratio (BXX) in the fuel blend [22]. Various biomass feedstocks can be used to produce biodiesel, and therefore, each biodiesel feedstock must be thoroughly studied. In the present work, Salacca zalacca seed oil was studied for its potential as biodiesel feedstock. Salacca zalacca plant is a palm tree commonly found in tropical countries and native to South Sumatra and

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Southwest Java, Indonesia [23, 24]. The plant produces fruit known as snake fruit which is referred to as salak in Indonesia and Malaysia. The abundance of the Salacca zalacca plant in Indonesia suggests a substantial economic gain in using its seed oil as a biodiesel feedstock. Furthermore, the Ministry of Energy and Mineral Resources, Republic of Indonesia, has mandated the use of biodiesel with a biodiesel-to-diesel ratio as high as 30:70 (30% biodiesel in the fuel composition, B30) at the year 2020 to 2025 [25]. The present study can help fulfil the mandate by suggesting Salacca zalacca seed oil as an alternative biodiesel feedstock that can be easily produced in Indonesia.

Despite the abundance of Salacca zalacca in Indonesia and across Southeast Asia, there is a lack of studies regarding the potential of Salacca zalacca plant as a biofuel feedstock. Yasin et al. [26] researched bioethanol production, which is another type of biofuel, from rejected Salacca zalacca fruit. More recent work by Idris and Novalia [27] investigated the distillation process to produce bioethanol from mixtures of Salacca zalacca fruit and coconut water. A study by Irawati et al. [28] is more closely related to the present work since they characterized and compared the properties of Salacca zalacca seed oil from two different cultivars. As far as the present authors are aware, no study has reported the engine performances of biodiesel produced from Salacca zalacca seed oil.

Due to the lack of studies and the need for a more thorough investigation, the present work investigated the fuel properties and engine performances of biodiesel derived from Salacca zalacca seed oil. In this study, Salacca zalacca methyl ester was produced and blended with the conventional diesel fuel at a biodiesel-to-diesel ratio of 10:90 and 20:80 (10% biodiesel or B10 and 20% biodiesel or B20 in the fuel composition, respectively). The produced biodiesel blends were tested for their fuel properties and used in a diesel engine to determine their engine performances. The results were compared with the fuel properties and engine performances of the conventional diesel fuel and various biodiesel standards to indicate the potential of the biodiesel blends to replace the fossil fuel.

METHODS

Biodiesel Production

Salacca zalacca seeds were cleaned using water and dried naturally under sunlight for 7 to 9 days. Afterwards, the seeds were further dried using an oven at 100 °C for 1 to 1.5 hours. The dried seeds underwent pulverization to become fine powder and had their oil extracted using the Soxhlet method with n-hexane as the solvent. Afterwards, the mixture of seed oil and n-hexane was evaporated using a heated rotary evaporator to separate the oil and n-hexane. After the evaporation process, the purified seed oil was converted into methyl ester through the transesterification process. The process used KOH (1% wt of the seed oil) as catalyst, and methanol (99.9% purity, 20% wt of the seed oil) as solvent. The oil, catalyst, and solvent were mixed using a heated magnetic stirrer at 60 °C. The mixture was then left at room temperature for 24 hours to separate the glycerol from the methyl ester. The separated methyl ester was heated to remove the remaining n-hexane and methanol. Afterwards, the methyl ester was combined with the conventional diesel fuel to produce B10 (10% biodiesel in the fuel composition) and B20 (20% biodiesel in the fuel composition).

Fuel Property Studies

The fuel properties of B10 and B20 tested include the density, kinematic viscosity at 40 °C, flash point Pensky Martin Closed Cup (PMcc), pour point, distillation temperature at 90% recovery, Sulphur content, water content (coulometric Karl Fischer titration), CCI (calculated cetane index), and HHV (higher heating value). Those properties were investigated following the regulation set by the Indonesian Directorate General of Oil and Gas 978.K/10/DJM.S/2006 on 19 November 2013 [29]. Except for HHV, all tests were performed in UPPS Laboratory of Pertamina (Indonesia's state-owned oil and natural gas firm) under ASTM standards. HHV measurement was performed in-house using an oxygen bomb calorimeter available at the Automotive Laboratory, Petra Christian University. Details on the ASTM standards, units, and the uncertainties are given in Table 1. The uncertainty is mainly based on the reported reproducibility in the Indonesian Biodiesel Standard SNI 7182:2015 document [30]. Reproducibility is defined as the difference in the measurements between two different operators using the same sample and under the same condition. For parameters where the reproducibility value is not explicitly provided, the uncertainty is estimated from the average uncertainties of the instruments, as reported in the document. It should be noted that the SNI 7182:2015 standard does not regulate the pour point, and therefore the uncertainty of cloud point was used instead. It is a reasonable substitute as they are measured using the same instrument but under a different criterion. As HHV was measured in-house, the uncertainty is based on the average uncertainty of six different types of fuel samples results, with three replications each.

Engine Performance Studies

The engine performance studies were conducted in the Automotive Laboratory, Petra Christian University using four cylinders and four strokes diesel engine (Isuzu 4JA - I. OHV) connected to a water brake dynamometer (Zollner-Kiel 3n19A). The engine and the water brake dynamometer specifications are given in Tables 2 and 3, respectively. The experiment was initially conducted by setting the engine speed to 3000 RPM and brake load of 0%. Afterwards, the brake load was increased to reduce the engine speed by a decrement of 200 RPM until the engine speed reached 1800 RPM. The engine load shown by the dynamometer, the time needed to consume 50 ml of the fuel, the room temperature, and the room humidity were recorded for each engine speed. From the recorded data, the torque, power, BMEP (brake mean effective pressure), BSFC (brake specific fuel consumption), and the thermal efficiency were determined. The experiments were performed for two repetitions for each engine speed, and the average was taken as the measurement. The uncertainty of the measurement is based on the largest and smallest values of the two repetitions.

TABLE 1. Details on the fuel property studies.

Property	Unit	Standard	Uncertainty	Note on the uncertainty
Density	kg/m^3	ASTM D - 1298	1.2	From the reported reproducibility, as given in [30]
Kinematic viscosity at 40 °C	cSt	ASTM D - 445	0.05584 – 0.07872	From the reported reproducibility that is dependent on the measured viscosity, as given in [30]
Flash point PMcc	°C	ASTM D - 93	3.5	From the reported reproducibility, as given in [30]
Pour point	°C	ASTM D - 97	3	Based on the cloud point reproducibility, as given in [30].
Distillation temperature at 90% recovery	°C	ASTM D - 86	11 – 15.22 %	From the reported reproducibility that is dependent on the temperature / recovered volume ratio, as given in [30]
Sulphur content	% wt	ASTM D - 4294	4.44 %	Estimated from the average uncertainty of the instruments, as given in [30]
Water content	ppm	ASTM D - 6304	5.75 %	Estimated from the average uncertainty of the instruments, as given in [30]
CCI (calculated cetane index)	-	ASTM D - 4737	6.38 – 6.844	From the reported reproducibility that is dependent on the measured CCI, as given in [30]
HHV (higher heating value)	MJ/kg	-	3.98%	Estimated from the average uncertainty of six different types of fuel samples, with three replications each.

TABLE 2. Engine specifications.

Specification	Value / Information	Specification	Value / Information
Bore and stroke	93 and 92 mm	Fuel injection technique	Direct injection
Volume of the cylinder	2499 cm^3	Fuel injection timing	12° before TDC
Compression ratio	18.4	Initial nozzle pressure	182 kg/cm^2
Compression pressure	31 kg/cm^2	Nozzle type	Hole
Idling speed	750 RPM	Number of holes in a nozzle	4
Highest power	86 ps or 64.2 kW	Cooling technique	Water cooling
Highest engine speed	3900 RPM	Engine cooling system	Radiator
Highest torque	172 Nm	Lubrication technique	Forced lubrication

TABLE 3. Specifications of the water brake dynamometer.

Specification	Value / Information
Type	Zollner-Kiel 3n19A
Rotational direction	Single direction
Number of impellers	One impeller
Maximum Rotational Speed	7500 RPM
Maximum power output	120 kW
Weight balancer	Sluice gate

RESULTS AND DISCUSSION

Fuel Property Results

The fuel property results for B10 and B20 are shown in Fig. 1. The properties were analyzed by comparing them with the biodiesel standards of ASTM D6751, EN 14214, and the Indonesian biodiesel standard SNI 7182:2015 [30, 31, 32]. The fuel properties of the conventional diesel fuel and palm oil biodiesel obtained from the previous study [13] were also shown for comparison. For ease of discussion, the conventional diesel fuel and palm oil biodiesel are abbreviated as CDF and POB, respectively. CDF is excluded from the comparison with the biodiesel standards as it is not a biodiesel fuel.

Figure 1(a) shows the measured density for the four fuels tested. The densities of B10 and B20 are slightly higher compared to the densities of CDF and POB. Compared with the biodiesel standards, the densities of B10 and B20 are lower than the biodiesel standard of ASTM D6751 (at least 880 kg/m3) [31]. Compared with the biodiesel standard of EN 14214 (860-900 kg/m3) [31], only B20 fulfils the requirement. Nevertheless, the densities of B10 and B20 are within the SNI 7182:2015 (850-900 kg/m3) [30], suggesting that biodiesels derived from Salacca zalacca seed oil can be used in Indonesia. CDF has a lower density than the biodiesels, which is generally the case. According to the Ministry of Energy and Mineral Resources, Republic of Indonesia [29], the density of CDF tested in this study fulfils the national requirement as it is within 815-860 kg/m3.

Figure 1(b) shows the kinematic viscosity of the fuels. Compared to CDF, the three biodiesels have significantly higher kinematic viscosity. This is an undesired property since higher viscosity may result in difficulty for the fuel to flow. Nevertheless, the kinematic viscosity of B10 and B20 are within the biodiesel standards of ASTM D6751 (1.90-6.00 cSt) [31], EN 14214 (3.50-5.00 cSt) [31], and SNI 7182:2015 (2.3-6.0 cSt) [30].

Figure 1(c) shows the results for flash point test. The results show that the three biodiesels tend to have a lower flash point compared to the CDF. Since flash point indicates the lower temperature limit to combust the fuel mixture, a minimum threshold for flash point is usually set for safety. Based on the ASTM D6751 (100-170 ºC) [31], EN 14214 (at least 120 ºC) [31], and SNI 7182:2015 (at least 100 ºC) [30] standards, none of the biodiesels fulfil the requirements. Additives may improve the flash point of the biodiesels to fulfil the standards [33].

Figure 1(d) shows the pour point of the four fuels. Except for POB, all fuels have a negative pour point. Pour point indicates temperature where the fuel starts to lose its ability to flow; lower pour point means that the fuel has more resistance to cold temperature. The pour points of all biodiesels are within the ASTM D6751 standard (-15 to 16 ºC) [31]. EN 14214 and SNI 7182:2015 do not have a pour point requirement [30, 31,32].

Figure 1(e) shows the distillation temperature at 90% recovery results. The distillation temperatures of the three biodiesels are significantly higher compared to the CDF. Higher distillation temperature indicates lower volatility that is associated with better fuel economy. On the other hand, lower distillation temperature, which indicates higher volatility, may result in better engine performances [34]. EN 14214 do not set a requirement for the distillation temperature at 90% recovery. ASTM D6751 and SNI 7182:2015 set a maximum value of 360 °C for the distillation temperature at 90% recovery, and none of the biodiesels tested fulfils the requirement [30, 32]. The distillation temperature may be reduced by increasing the ratio of the CDF in the Salacca zalacca biodiesel blend.

Figure 1(f) shows the Sulphur content of the four fuels. It shows that the three biodiesel fuels have significantly higher Sulphur content, with B10 reaching as high as 0.206% wt. The Sulphur content should be as low as possible to prevent corrosion and unwanted Sulphur-based emissions. None of the biodiesels tested fulfill the ASTM D6751 (<150 ppm or 0.015%wt) [31], EN 14214 (<10 ppm or 0.01%wt) [31], and SNI 7182:2015 (<50 mg/kg or 0.005%wt) [30] standards. Nevertheless, B20 reached 0.165% wt, which is close to POB that has been commercially available in Indonesia. Increasing the CDF content in the Salacca zalacca biodiesel blends may lower the Sulphur content.

Figure 1(g) shows the water content of the four fuels tested. Fuel with lower water content has better energy output since water may reduce the generated heat from combusting the fuel. Hence, lower water content is desired. Unfortunately, B20 is shown to have a significantly larger water content compared to the other fuels tested. Nevertheless, the water contents of the biodiesels are within the standards of EN 14214 [31] and SNI 7182:2015 [30] (< 0.05% vol or 500 ppm). None of the biodiesels adheres to the ASTM D6751 standard (<0.005% vol or 50 ppm of water and sediment) [31].

Figure 1(h) shows the CCI of the four tested fuels. Higher CCI improves the knocking behavior of the fuel when combusted in an engine. The CCIs are close to one another except for POB, which has a slightly larger CCI of 55. It shows that the addition of Salacca zalacca seed oil up to 20% of the fuel composition have a small effect on the CCI.

The CCIs of the biodiesels adhere to ASTM D6751 (at least 47) [31], EN 14214 (at least 51) [31], and SNI 7182:2015 (at least 51) [30] standards.

Figure 1(i) shows the HHV of the four fuels. The biodiesels have larger HHV, which means that they have higher energy output when combusted. Increasing the biodiesel content from 10% to 20% of the fuel composition (from B10 to B20) improves the HHV. None of the three standards used in this study for comparison regulates the HHV [30, 31, 32].

Analysis of the fuel properties suggests that not all of the properties of B10 and B20 investigated adhere to the biodiesel standards. In particular, the flash point, distillation temperature, and Sulphur content should be improved. The summary of the comparison with the biodiesel standards is shown in Table 4. Furthermore, for some fuel properties, the value of B10 does not correspond to the intermediate between CDF and B20, which is a reasonable assumption and suggest a discrepancy. Those properties are the pour point, distillation temperature, Sulphur content, water content, and the CCI. For the distillation temperature and CCI, the uncertainties of B10 and B20 intersect and explain the discrepancy. This is not the case for the pour point, Sulphur content, and water content. The discrepancy of those three properties may have originated from the variability of the feedstock. While all feedstock was obtained from the same vendor, the vendor may have sourced their feedstock from different plantations, resulting in varying feedstock quality and content. The water content of the feedstock for B10 may have been lower than B20, leading to lower water content for B10, higher weight percentage of the Sulphur content for B10, and affecting the pour point to a degree. The Sulphur content may also be higher for B10 feedstock, exacerbating the discrepancy of the Sulphur content.

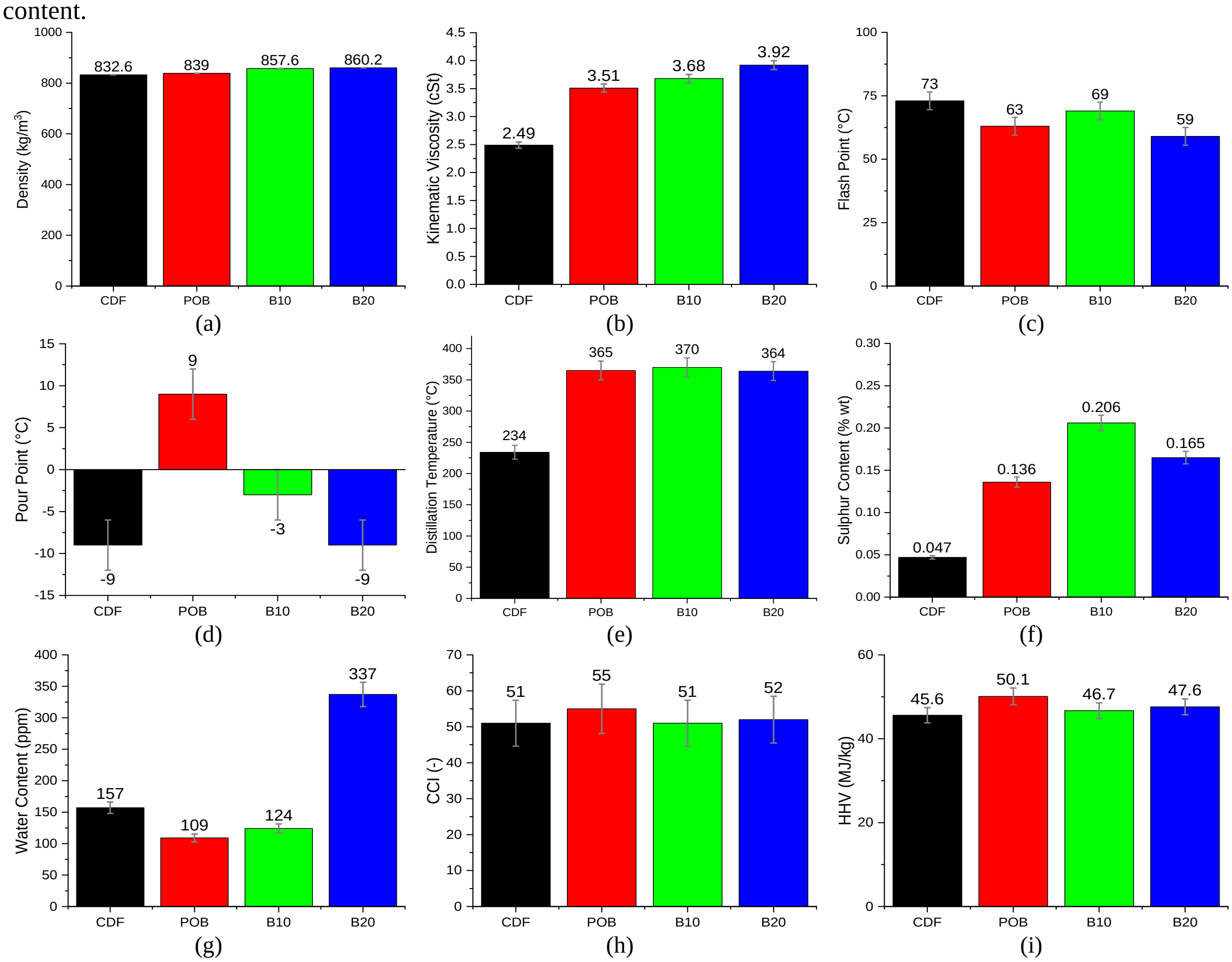

FIGURE 1. Results of the fuel property tests for (a) density, (b) kinematic viscosity, (c) flash point, (d), pour point, (e) distillation temperature, (f) Sulphur content, (g) water content, (h) CCI (calculated cetane index), and (i) HHV (higher heating value). CDF and POB are abbreviation of the conventional diesel fuel and palm oil biodiesel, respectively. The error bars for density results are not clearly visible since the uncertainty of the measurements is small.

TABLE 4. Summary of the comparison with the biodiesel standards. HHV is excluded from the table as the three biodiesel standards do not regulate it.

Properties	Fuel	ASTM D6751	EN 14214	SNI 7182:2015
Density	POB	X	X	X
	B10	X	X	O
	B20	X	O	O
Kinematic viscosity	POB	O	O	O
	B10	O	O	O
	B20	O	O	O
Flash point	POB	X	X	X
	B10	X	X	X
	B20	X	X	X
Pour point	POB	O	NA	NA
	B10	O	NA	NA
	B20	O	NA	NA
Distillation temperature	POB	X	NA	X
	B10	X	NA	X
	B20	X	NA	X
Sulphur content	POB	X	X	X
	B10	X	X	X
	B20	X	X	X
Water content	POB	X	O	O
	B10	X	O	O
	B20	X	O	O
Calculated cetane index	POB	O	O	O
	B10	O	O	O
	B20	O	O	O

X: does not meet the requirement; O: meet the requirement; NA: not applicable.

Engine Performance Results

The engine performance results for the four fuels are shown in Fig. 2. Unlike the fuel property results, the engine performances of CDF and POB were not adopted from the previous study. They were obtained from experiments conducted in the present work.

Figure 2(a) shows the torque as a function of the engine speed. CDF and B10 have similar torque values, while POB has lower torque and B20 has even lower torque than POB. The power and BMEP of the engine, as given in Figs. 2(b) and 2(c), also show a similar trend as the torque since the three parameters are closely related. The results from Figs. 2(a), 2(b), and 2(c) are in contrast with the high CCI and HHV for POB and B20, as shown in Figs. 1(h) and 1(i), respectively. B20 may have lower performance due to its significant water content, reducing the heat release rate and decreasing the engine output. The low flash point of POB and B20 may cause misfiring and reduces their engine performances. It suggests that various properties of the fuel can affect the torque, power, and BMEP.

Figure 2(d) shows the BSFC of the engine as a function of the engine speed. At low engine speed, B10 has the highest BSFC, indicating that the engine consumed a larger amount of B10 fuel compared to the others under the same condition. At engine speed above 2200 RPM, the BSFC of B20 abruptly increases, resulting in a large BSFC at high engine speed. Other fuels also experience an abrupt increase in the BSFC, however, it occurs at a higher engine speed of 2800 RPM and above. Among the biodiesels studied, POB has the lowest BSFC at low to upper intermediate engine speed (1800 to 2600 RPM). At an engine speed of 2800 and 3000 RPM, B10 has a lower BSFC compared to POB.

The trends observed in the BSFC can be explained from the thermal efficiency shown in Fig. 2(e). At low engine speed, where B10 has a large BSFC, B10 also has the lowest thermal efficiency. The low thermal efficiency means that a larger amount of fuel is needed to generate the same engine output. At an engine speed of 2200 RPM and above, B20 experienced an abrupt decrease in its thermal efficiency, which resulted in the large BSFC for B20, as seen in Fig. 2(d). The abrupt increase in the BSFC of CDF, POB, and B10 can be explained by the abrupt decrease in the thermal efficiency at 2800 RPM and above.

Based on the engine performance results, B10 has engine performances comparable to that of CDF. However, there are issues in using B10 to replace CDF, such as the high BSFC and low thermal efficiency at low engine speed. Furthermore, based on the fuel property studies, B10 has a low flash point, high Sulphur content, and high distillation temperature that do not adhere to the biodiesel standards. These issues should be addressed before B10 can replace CDF. Feedstock pre-treatment and additives have been proposed to improve the fuel properties and engine performances of the fuel [33,35,36]. Future investigations may be conducted to observe the effect of employing those methods on biodiesel derived from *Salacca zalacca* seed oil.

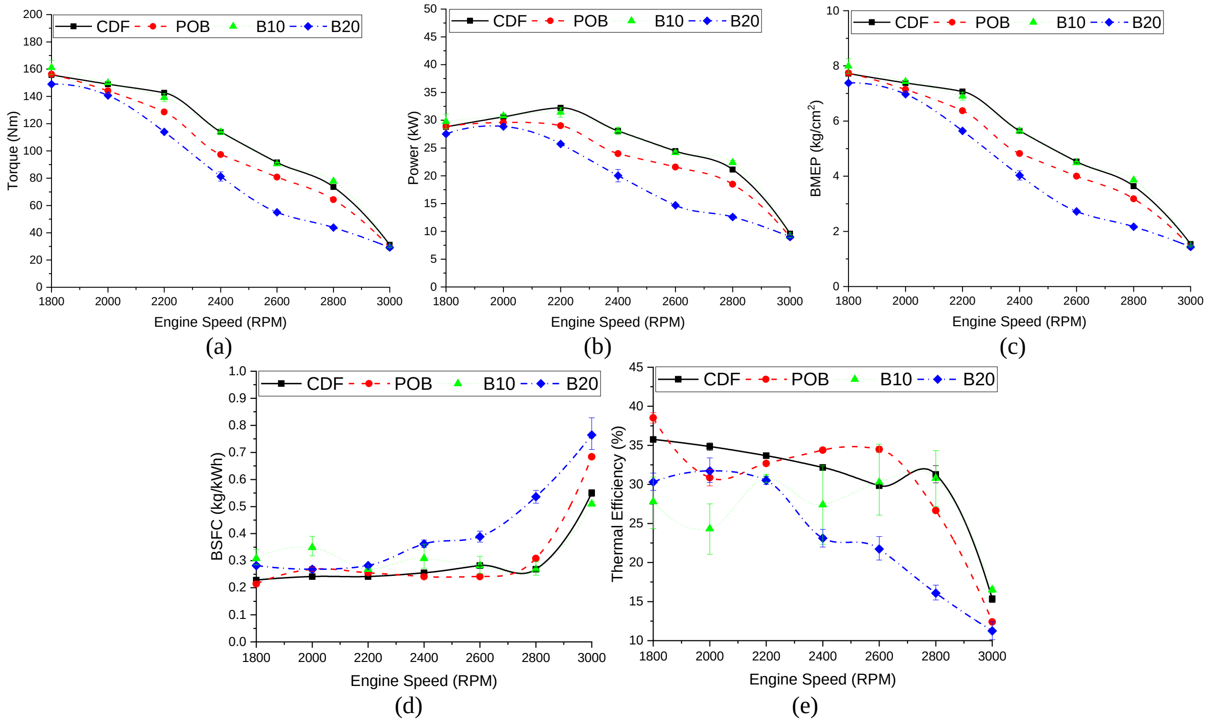

FIGURE 2. Results of the engine performance studies for (a) torque, (b) power, (c) BMEP (brake mean effective pressure), (d) BSFC (brake specific fuel consumption), and (e) thermal efficiency. CDF and POB are abbreviation of the conventional diesel fuel and palm oil biodiesel, respectively. Some of the error bars are not visible due to the small uncertainty of the measurements.

CONCLUSION

The fuel properties and engine performances of biodiesel blends derived from *Salacca zalacca* seed oil have been investigated. The study used blends with a biodiesel-to-diesel ratio of 10:90 (B10) and 20:80 (B20). The fuel property results suggest that the flash point, distillation temperature at 90% recovery, and Sulphur content of biodiesel derived from *Salacca zalacca* seed oil need to be improved. The improvement of those properties should refer to the biodiesel standards. B10 has comparable performances to conventional diesel fuel in terms of engine performances, suggesting that B10 can replace the conventional diesel fuel. However, the brake specific fuel consumption and thermal efficiency of B10 suffer at low engine speed. Future studies should focus on improving the fuel properties and engine performances of biodiesel derived from *Salacca zalacca* seed oil.

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