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Combustion analysis of microalgae methyl ester in a common rail direct injection diesel engine

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HIGHLIGHTS

- Microalgae oil Methyl ester combustion performance is comparable with petroleum diesel.
- Very long chain fatty acids increase the fuel density and decrease the cetane number.
- Microalgae oil methyl ester reduce unburned hydrocarbon emission significantly.

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ABSTRACT

In this study, the biodiesel properties and effects of blends of oil methyl ester petroleum diesel on a CI direct injection diesel engine is investigated. Blends were obtained from the marine dinoflagellate *Crypthecodinium cohnii* and waste cooking oil. The experiment was conducted using a four-cylinder, turbocharged common rail direct injection diesel engine at four loads (25%, 50%, 75% and 100%). Three blends (10%, 20% and 50%) of microalgae oil methyl ester and a 20% blend of waste cooking oil methyl ester were compared to petroleum diesel. To establish suitability of the fuels for a CI engine, the effects of the three microalgae fuel blends at different engine loads were assessed by measuring engine performance, i.e. mean effective pressure (IMEP), brake mean effective pressure (BMEP), in cylinder pressure, maximum pressure rise rate, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), heat release rate and gaseous emissions (NO, NO_x, and unburned hydrocarbons (UHC)). Results were then compared to engine performance characteristics for operation with a 20% waste cooking oil/petroleum diesel blend and petroleum diesel. In addition, physical and chemical properties of the fuels were measured. Use of microalgae methyl ester reduced the instantaneous cylinder pressure and engine output torque, when compared to that of petroleum diesel, by a maximum of 4.5% at 50% blend at full throttle. The lower calorific value of the microalgae oil methyl ester blends increased the BSFC, which ultimately reduced the BTE by up to 4% at higher loads. Minor reductions of IMEP and BMEP were recorded for both the microalgae and the waste cooking oil methyl ester blends at low loads, with a maximum of 7% reduction at 75% load compared to petroleum diesel. Furthermore, compared to petroleum diesel, gaseous emissions of NO and NO_x, increased for operations with biodiesel blends. At full load, NO and NO_x emissions increased by 22% when 50% microalgae blends were used. Petroleum diesel and a 20% blend of waste cooking oil methyl ester had emissions of UHC that were similar, but those of microalgae oil methyl ester/petroleum diesel blends were reduced by at least 50% for all blends and engine conditions. The tested microalgae methyl esters contain some long-chain, polyunsaturated fatty acid methyl esters (FAMEs) (C22:5 and C22:6) not commonly

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found in terrestrial-crop-derived biodiesels yet all fuel properties were satisfied or were very close to the ASTM 6751-12 and EN14214 standards. Therefore, *C. cohnii*- derived microalgae biodiesel/petroleum blends of up to 50% are projected to meet all fuel property standards and, engine performance and emission results from this study clearly show its suitability for regular use in diesel engines.

1. Introduction

Ever-diminishing global fossil fuel resources are increasing pressure to find sustainable alternative fuels and reduce dependency on fossil fuels. Mono alkyl esters of fatty acids traditionally obtained from vegetable oil are referred to as biodiesel. Biodegradability, renewability and low net carbon emission characteristics of biodiesel have generated significant interest in biodiesel, as a replacement option for petroleum diesel [15]. As a result, a number of studies compared combustion and emission performance of various biodiesel with petroleum diesel [13,9,29,17,24,32,33,50,8] and engine performance and emissions tests for vegetable oils have been reviewed recently [18].

Various chemical and physical properties of biodiesel contribute to engine performance and emission characteristics. Biodiesel often contains around 10% oxygen by mass, which influences its combustion performance and emissions significantly. In addition, biodiesel use results in reduction of emissions of unburned hydrocarbons (UHC), particulate matter (PM) and carbon monoxide (CO) [1,13,9,42,34,44]. However, generally, biodiesel use results in an increase in NO_x emissions [1,27,42,44,35,48]. Previous research has shown that microalgae oil methyl ester properties can satisfy biodiesel standards ASTM 6751-12 and EN14214, and use of this fuel should be comparable with petroleum diesel. However, the qualities of microalgae oil methyl esters vary with environmental conditions, and fatty acid composition of the oil is additionally strain-dependent. The performance of microalgae methyl ester in an actual engine has only been reported in the literature in the last year or so. *Ankistrodesmus braunii* and *Nannochloropsis* sp. were tested in a single cylinder Ricardo-E6 engine and found with slight reduction of engine torque with higher-pressure rise rate and heat release rate than that of petroleum diesel [20]. The emission characteristics, of microalgae methyl ester from *Chlorella vulgaris* was reported with reduced UHC and increase of NO_x while tested in a single cylinder Kirloskar engine [36]. Both the fuels have lower density but almost similar kinematic viscosity than that of microalgae methyl ester from this study. However, *Crypthecodinium cohnii* in this study contains high amounts of very long chain polyunsaturated fatty acids (C22:5 and C22:6) compared to *A. braunii* and *Nannochloropsis* sp. from [20] could alter the results.

A significant amount of publications report on the possibility of using microalgae as a potential source for biodiesel [46,49,14,23,45,20], as microalgal biodiesel does not compete with global food supplies [16]. It is also suggested that microalgae can produce 18,927 L of biodiesel per 242,812 m^2 compared to 227 L of soy-derived biodiesel per year [16]. The benefits of microalgae include rapid growth, high capacity of CO_2 fixation, and the possibility of intensive culture on non-arable land with smaller area requirements than terrestrial crops. These factors have all contributed to the current focus on algae research. However, a very limited number of works have been published with investigation of the physical and chemical properties, engine performance, and emission analysis of actual microalgae fuel in the modern diesel engine [47,36,43].

Therefore, the main objectives of this study are to detail the physical and chemical properties of the microalgal biodiesel and to investigate engine performance, which is then compared to petroleum diesel and a 20% waste cooking oil biodiesel/petroleum diesel blend. Biodiesel blend B20 is recognised an optimum-level blend because it represents a good balance of engine performance, fuel consumption, emission reduction and long-term storage ability than any other blend [11,6]. Chemical and physical properties of microalgal and waste cooking oil methyl esters were investigated, according to biodiesel standards ASTM 6751-12 and EN 14214 (Tables 1 and 2). A four-cylinder, turbo-charged diesel engine equipped with engine performance and emission instrumentation was used to investigate the effect of microalgal/petroleum diesel blends (10%, 20%, and 50%); waste cooking oil methyl ester/petroleum diesel blend (20%) and petroleum diesel were used as reference fuels.

The performance of the engine output is presented in terms of engine cylinder pressure, maximum pressure rise rate, indicated mean effective pressure (IMEP), brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and heat release rate. Gaseous emissions of nitric oxide (NO), nitrogen oxide (NO_x) and unburned hydrocarbons (UHC) are also presented for microalgae methyl ester/petroleum diesel blends, which are compared to petroleum diesel and the waste cooking oil methyl ester/petroleum diesel blend.

2. Materials and methods

2.1. Preparation of microalgae oil methyl ester

Dry microalgae biomass (heterotrophic dinoflagellate*: C. cohnii*) was obtained from Martek Biosciences Corporation, USA. A pilot-scale oil extraction from these microalgae was carried out with analytical grade n-hexane, in the Plant Science Laboratory of Southern Cross University, NSW, Australia. Before transesterification, the oil acid value was tested and found to be very low (below 0.2 mg. KOH g^{-1}), making it suitable for transesterification without soap formation. Total extracted lipids were divided into 2 L aliquots in a 5 L glass beaker on a magnetic stirrer hot plate. An amount of 15.8 g of 85% KOH was dissolved in 250 mL of 99.8% methanol, and slowly added to the oil at 55 °C, stirring constantly. The detailed process can be found in [26].

2.2. Experimental test fuels

Fuel properties, engine performance and emissions of microalgae biodiesel/petroleum diesel blends were compared with a 20% blend of waste cooking oil methyl ester/petroleum diesel and petroleum diesel. Microalgae biodiesel was prepared in three different blends by weight 10%, 20% and 50% and designated as D90A10, D80A20 and D50A50, respectively. A single blend with 20% waste cooking oil methyl ester was prepared and designated as D80WCO20. Microalgae fatty acid methyl ester composition was determined by GC/MS in the Plant Science Laboratory of Southern Cross University, NSW, Australia. Dry microalgae biomass was extracted in pilot-scale with the non-polar solvent n-hexane. The extracted lipid was transesterified and converted to fatty acid methyl ester. The EcoTech Biodiesel Company in Brisbane supplied waste cooking oil methyl esters. The composition of the pure fatty acid methyl esters of these two biodiesels were measured according

Table 1
Fatty acid composition (g 100 g^{-1} FAME) of biodiesels.

FAME	Microalgae		Waste cooking oil	
	Average	Standard deviation	Average	Standard deviation
C14:0	8.30	0.1	0.00	0.00
C16:0	22.20	0.23	11.2	2.04
C18:0	0.56	0.05	3.50	0.50
C18:1(Tran)	0.00	0.00	2.70	0.76
C18:1 (cis)	0.00	0.00	64.4	4.23
C18:2(cis-9,12)	0.00	0.00	18.3	1.03
C18:3(all cis 6,9,12)	0.41	0.04	0.00	0.00
C20:3	0.50	0.03	0.00	0.00
C20:4	0.70	0.02	0.00	0.00
C20:5 (EPA)	1.70	0.08	0.00	0.00
C22:5	17.90	0.06	0.00	0.00
C22:6 (DHA)	47.70	0.41	0.00	0.00
SFAs	31.06		14.72	
MUFA	0.00		67.03	
PUFA	68.94		18.25	

to the procedure detailed in [25] and are presented with the corresponding standard deviation of three measurements in Table 1. The microalgae methyl ester contains large amount of very long chain poly unsaturated fatty acids (C22:5, C22:6) compared to other conventional biodiesels. Waste cooking oil biodiesel was chosen to compare with the performance of microalgae biodiesel is one of the most commonly used biodiesel not containing those long chain poly unsaturated fatty acids.

2.3. Fuel properties

Biodiesel properties of the extracted pure methyl esters were analysed at the Caltex Refinery Laboratories in Wynnum, Brisbane, according to standard test procedures. The results are shown in Table 2, in compliance with the biodiesel standards ASTM 6751-12 and EN14214. Calorific values and lower heating values of both biodiesels were around 10% less than for petroleum diesel, whereas density and kinematic viscosity of both biodiesels were up to 7.8% and 47.8% higher, respectively, than for petroleum diesel. Oxygen, hydrogen and carbon content of the microalgae biodiesel were 10.47%, 11.12% and 78.41%, with similar values for waste cooking oil biodiesel (10.93%, 12.21% and 76.93%, respectively). Oxygen content in biodiesel provides advantages for combustion, whereas higher density, viscosity and lower calorific value may be disadvantageous for biodiesel. The stoichiometric air fuel ratios of tested fuels were within the range 13.8:1–15.1:1 as shown in Table 4. Typically, modern common rail turbo-charged diesel engines have air fuel ratios above 25:1 under load. Thus, the effect of stoichiometric ratio variation on engine performance in such an engine is expected to be small because of the large amount of excess air present.

2.4. Experimental setup

All experiments were conducted with a four-cylinder, turbo-charged diesel engine (specifications as per Table 3). The power output of the engine was measured with an eddy current dynamometer. The engine was run at 2000 rpm with four different loads – 25%, 50%, 75% and 100%. For the present investigation, 100% load is defined as the maximum load, which the engine could achieve at a fixed engine speed with full throttle. Intermediate loads were calculated accordingly. Details of the engine operating conditions are shown in Table 4.

All engine tests were run with a Froude Hofmann AG 150 eddy current dynamometer, which was embedded with TEXCEL-V12 software for precise digital control and sophisticated data acquisition. An open Simtek Bodylogic Engine control module (ECU) + IDM (Injector driver module) was used. Engine and injection parameters were carefully controlled during the experiment by use of a constant engine map. The measurement accuracy for the torque was ±1.25 Nm (±0.25% of full-scale load) and ±1 rpm for speed. A schematic diagram of the test set-up is shown in Fig. 1. The in-cylinder gas pressure was recorded with a Kistler piezostar pressure sensor (Type 6056A42). The pressure transducer outputs were amplified and converted to digital signals and recorded for every 0.5°CA. The crank angle was measured by Valeo, model PA66 GF30 Hall-Effect sensor with 250 mV output voltage, sensitivity 5.0 mV/gauss and switching speed 3 ms. Such Hall-Effect sensors are the most common crank angle sensor in modern engines and typically have accuracy better than ±0.05 degrees. In order to eliminate the effect of cycle-to-cycle variations, the in-cylinder pressure data were recorded for 100 consecutive cycles and the mean was used for analysis.

To measure engine emissions, exhaust gas was sampled after it had passed through the exhaust manifold. A fraction of the sampled gas was delivered to the gas analysers via flexible copper tubing, equipped with a water trap for NO_x and UHC measurements. A CAI600 series analyser was used to measure the UHC equivalent to propane (C_3H_8). A CAI600 series CLD NO_x analyser was used for NO and NO_x measurements. An in depth emission analysis of the particle matter emission will be published in a separate paper.

3. Results and discussion

The impact of microalgae biodiesel/petroleum blend fuel was compared with a 20%waste cooking oil methyl ester/petroleum diesel blend and petroleum diesel. Engine performance at partial to full load conditions was studied based on combustion characteristics. Cylinder pressure, maximum pressure rise rate, indicated mean effective pressure (IMEP), brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), heat release rate (HRR) and the cylinder pressure-crank angle indicator diagram were investigated with different blend percentages and different loads.

3.1. Impact of fatty acids composition on fuel properties

The pure microalgae oil methyl ester of *C. cohnii* used in this study has kinematic viscosity of 5.06 $mm^2\,s^{-1}$ and density of 0.912 kg L^{-1} which are both slightly higher compared to that of waste cooking oil methyl ester at 4.82 $mm^2\,s^{-1}$ and 0.87 kg L^{-1}, respectively. This is mainly due to the higher amount of very long

Table 2
Properties of pure fatty acid methyl esters (FAME) and petroleum diesel and compliance with the requirements of ASTM 6751-12 and EN 14214 biodiesel standards.

Fuel property	Test method	Unit	Microalgae oil methyl ester	Waste cooking oil methyl ester	Biodiesel Standard ASTM 6751-12	Biodiesel Standard EN 14214	Petroleum diesel
CN	DIN 51773	–	46.5	58.6	47 min	51	53.3
Kinematic viscosity @40 °C	ASTM D445	mm^2/s	5.06	4.82	1.9–6.0	3.5–5.0	2.64
Density @15 °C	ASTM D4052	kg/L	0.912	0.87	0.86–0.90	0.86–0.90	0.84
HHV	–	MJ/kg	39.86	39.9	–		–
LHV	–	MJ/kg	37.42	37.2	–		44.0
Acid value	ASTM D974	mg KOH/g	0.14	–	0.5max	0.5max	0.0
Flash point (close cup)	ASTM D93	°C	95.0	–	93min	–	71.0
Flash point	ASTM D93	°C	–	⩾180	130	120	–
Sulphurcontent	ASTM D7039	mg/kg	7.5	–	15max	10max	5.9
Cloud point	IP 309	°C	16.1	–	Report	Report	4.0
Lubricity @°60	IP 405	mm	0.136	–	–	–	0.406
Copper corrosion (3 h @50°C)	ASTM D130		1a	–	1max	1 max	1a
Water sediment	ASTM D2709	vol%	0	–	0.005% max	0.005% max	0.0
10% Recovered	ASTM D86	°C	–	–	–	–	222.4
50% Recovered	ASTM D86	°C	–	–	–	–	272.4
90% Recovered	ASTM D86	°C	–	–	–	–	331.1
95% Recovered	ASTM D86	°C	–	–	–	–	347.4
FBP	ASTM D86	°C	–	–	–	–	357.7
Oxygen content	–	wt.%	10.47	10.93	–	–	–
Hydrogen content	–	wt.%	11.12	12.21	–	–	–
Carbon content	–	wt.%	78.41	76.93	–	–	–

chain polyunsaturated fatty acids (C22:5 and C22:6 in Table 1), Other microalgae species, *A. braunii* and *Nannochloropsis* sp., with 78% saturated fatty acid, were reported to have a kinematic viscosity of 4.19 $mm^2\,s^{-1}$ and density of 0.869 $kg\,L^{-1}$ [20]. The present microalgae oil methyl ester had the highest density of microalgae fuel used in engine tests and reported in the literature so far. Higher density and kinematic viscosity of pure methyl ester of *C. cohnii* may result in a larger size of atomisation droplet with greater penetration into the cylinder and the lower cetane number which could explain the increased ignition delay observed in this study for microalgae oil methyl ester. Ignition delay for microalgae blends in this study is shown in Fig. 6(b–d). However, the BSFC of D80A20 increased ~5% which is not significantly different to that of other microalgae oil methyl ester with lower density (0.867 $kg\,L^{-1}$) [36]. It can be seen, even with a higher amount of very long chain fatty acids (C22:5, C22:6), that the combustion performance of the engine is comparable with petroleum diesel and other biodiesel.

3.2. Impact of biodiesel blends on cylinder pressure

Variation of cylinder pressures with respect to crank angle for the different blends of microalgae biodiesel D90A10, D80A20 and D50A50, waste cooking oil methyl ester D80WCOB20 and petroleum diesel (D100) at different engine loads (25%, 50%, 75% and 100%) are presented in Fig. 2(a–d). No significant differences in peak cylinder pressure were noted within biodiesel blends. However, at 25% engine load, cylinder peak pressure of D100 was up to 8% higher than the biodiesel blends; this could be due to the higher viscosity of biodiesel that is unfavourable as a fuel for combustion [20]. A slight increase of compression pressure for D100 before injection is seen at 25% load in Fig. 2a. This could be due to the air and fuel temperatures were not controlled by heat exchangers during the experiment. Therefore, such effects as changes in charge air mass due to inlet temperature variation may have occurred. This in turn will result in an increase in compression pressure before injection. However, any explicit correlation between cylinder pressure and the blend ratios could not be defined, as increase in load reduced the differences in cylinder pressure.

The pressure rise rate is a parameter closely related to ignition commencement. The microalgae biodiesel blends and waste cooking oil blend had a higher pressure rise rate than D100 at 25% engine load (Fig. 3). Increasing loads eliminated this difference at higher loads (Fig. 3). The longer the ignition delay period, the more liquid fuel is injected before ignition [20], so a higher mass of fuel ignites in a shorter time, thus increasing the pressure rise rate. Compared to petroleum diesel, the pure biodiesels had a higher density, viscosity and a lower cetane number, except waste cooking oil biodiesel, which had a higher cetane number (Table 2), leading to an increase of ignition delay, consequently increasing the

Table 3
Test Engine specifications.

Model	Peugeot 308 2.0 HDi
Cylinders	4
Compression ratio	18
Capacity	2.0 (L)
Bore × Stroke	85 × 88 (mm)
Maximum power	100 kW @ 4000 rpm
Maximum torque	320 Nm @ 2000 rpm
Aspiration	(Turbocharged) Intercooled
Fuel injection system	Common rail (Multiple fuel injection) Injection pressure: 1600 bar
Dynamometer	Froude Hofmann AG150 eddy current dynamometer

Table 4
Maximum load @2000 rpm with different fuel, test condition, date and time.

Fuel	Average torque (Nm) @ full load	Date and time of experiment commencement	Calculated CN*	Stoichiometric air–fuel ratio
D90A10	236	21/02/2014 (4:07PM)	53.3	14.8
D80A20	244	24/02/2014 (3:48PM)	52.6	14.5
D50A50	230	24/02/2014 (5:20PM)	51.9	13.8
D100	241	07/03/2014 (3:28PM)	49.9	15.1
D80WCO20	235	11/03/2014 (3:04 PM)	54.4	14.6

Calculated CN*: calculated from the cetane number of pure fuel blend ratio.

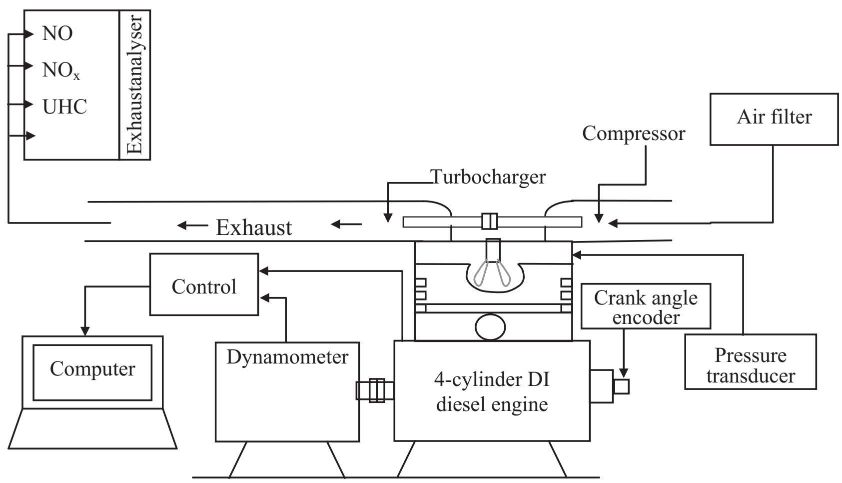


Fig. 1. Schematic diagram of test set-up.

pressure rise rate. The maximum pressure rise rate was higher at 100% engine loads because of rapid combustion, but it dropped unexpectedly for the D90A10 and D80WCO20.

3.3. Impact of biodiesel blends on IMEP, BMEP and FMEP

The uniform pressure that would be required throughout the power stroke of an engine, to do the same amount of work as is done by the varying pressures that are obtained during the stroke, is called indicated mean effective pressure (IMEP), whereas brake mean effective pressure (BMEP) is the work done per unit displacement volume of a single cylinder. IMEP, BMEP and frictional mean effective pressure (FMEP) were analysed to determine the effect of microalgae biodiesel blends in relation to a 20% waste cooking oil methyl ester/petroleum diesel blend D80WCO20 and petroleum diesel D100. IMEP and BMEP obtained from biodiesel blends did not vary by more than 3% compare to that of petroleum diesel D100 (Fig. 4). However, when the variation from petroleum diesel was calculated, biodiesel blends had typically lower IMEPs irrespective of engine load, except for the D80A20 blend, which had no significant variation from D100 at 25 and 50% engine loads, but IMEP decreased at higher engine loads (Fig. 4b). This is likely due to the higher calorific value of D100. As shown in Table 1, the microalgae fatty acid methyl esters and waste cooking oil methyl ester profiles had a high degree of polyunsaturation (65% C22:6 and C22:5) and 85%, respectively). This could lead to poor ignition quality and reduction of IMEP. However, the oxygen content in biodiesel enables complete combustion, which can increase the IMEP [38]. Data obtained here show that the D80A20 blend is comparable to D100 and shows better performance among other biodiesel blends tested. Perhaps due to an optimal combination of unsaturated fatty acids and oxygen content, that is providing the better combustion. However, it must be stated that fuel temperatures are not under identical conditions throughout these experiments. For example, maximum ambient temperatures on the day of the tests varied by 5 $^{\circ}$C. Therefore, a small part of the variation of IMEP and BMEP may not be fully attributable to biodiesel blends.

Fig. 4(a and c) shows that BMEP is following almost the same trend as IMEP, but the performance of microalgae biodiesel blends increased when compared to D80WCO20, especially D80A20, where the BMEP was found to be even better than D100 at 25% load. The FMEP of all biodiesel blends and petroleum diesel was around 0.2 MPa irrespective engine load. Impact of biodiesel blends on BSFC and BTE

BSFC is a parameter quantifying fuel efficiency. Fig. 5 shows the BSFC of the test engine operated with D100, D90A10, D80A20 D50A50 and D80WCO20 fuels at four different loads (25%, 50%, 75% and 100% load). Decreases of BSFC slowed with increased engine loads for all fuels, however, D50A50 had the highest BSFC at all engine loads, while the other microalgal biodiesel blends and the D80WCO20 had intermediate and similar BSFC trends compared to D100 and D50A50 BSFCs and were comparable at a 25% engine load (Fig. 5). The higher BSFC of biodiesel blends could be due to the lower calorific values compared to petroleum diesel [9,7,33,40,50,19]. The data shows that D50A50 is the least fuel-efficient blend with a $\sim$ 7.5% higher BSFC, compared to petroleum diesel at all engine loads. Yet the corresponding change in calorific values is 3.2%. The difference in the changes in BSFC and BTE is due to a variety of factors including combustion of oxygenated fuels and difference in calorific value.

In Table 2, the calorific value (LHV) of microalgae and waste cooking oil methyl esters is 15% lower when compared with petroleum diesel, in which it is larger than the observed 10% increase in the BSFC of biodiesel. This discrepancy could be due to the higher oxygen content of biodiesels, which leads to complete combustion, thereby minimising increases in BSFC [5].

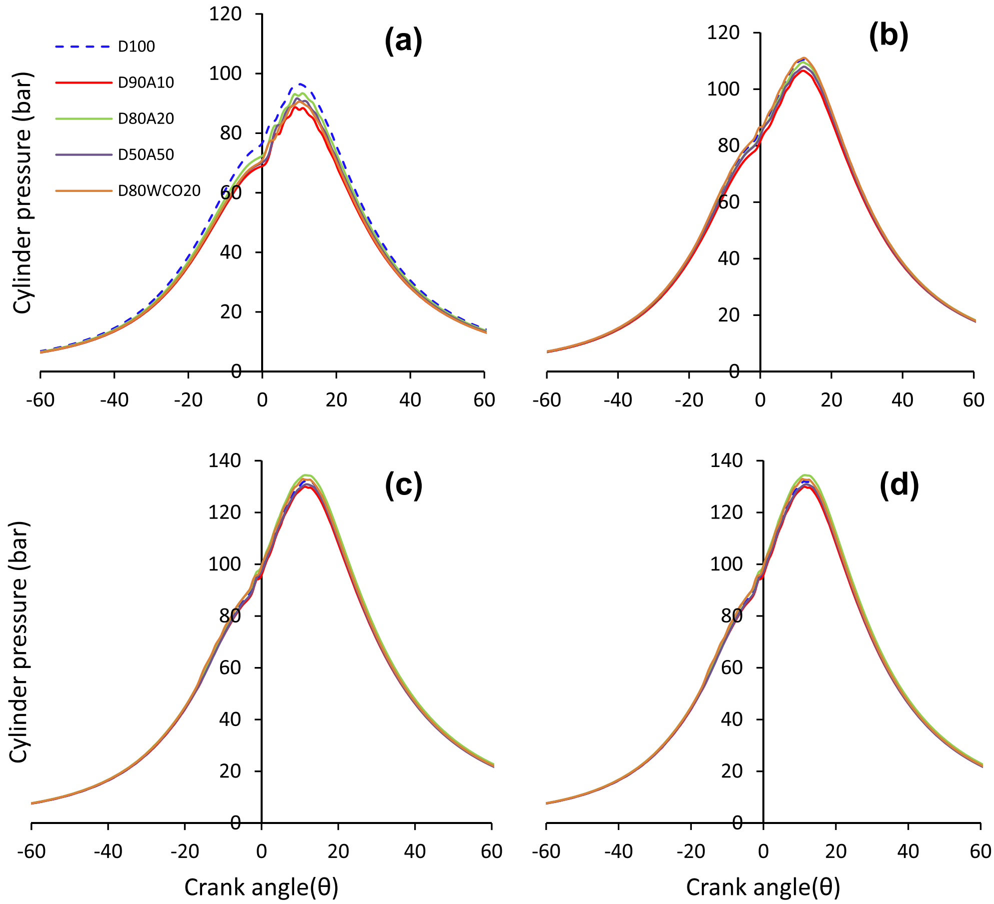
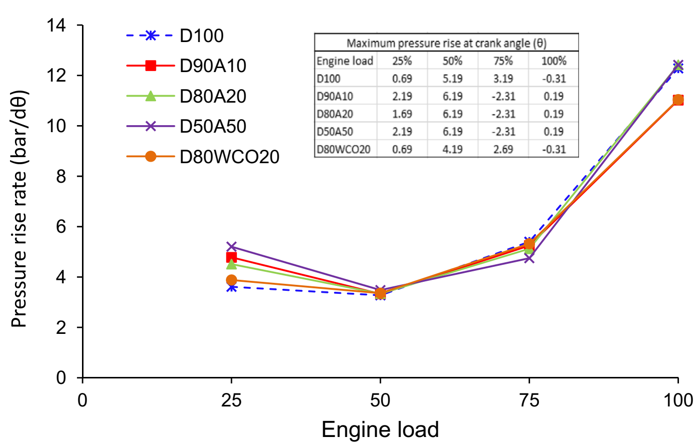


Fig. 2. Variation of cylinder pressures with crank angle at (a) 25% load, (b) 50% load, (c) 75% load, and (d) 100% loads for petroleum diesel and biodiesel blends.



Engine load	25%	50%	75%	100%
D100	0.69	5.19	3.19	-0.31
D90A10	2.19	6.19	-2.31	0.19
D80A20	1.69	6.19	-2.31	0.19
D50A50	2.19	6.19	-2.31	0.19
D80WCO20	0.69	4.19	2.69	-0.31

Fig. 3. Variation of pressure rise rates with varying engine loads for petroleum diesel and biodiesel blends.

Brake thermal efficiency (BTE) is a parameter to represent how efficiently an engine transforms the chemical energy of the fuel into useful work. This parameter is the ratio determined by brake power in the output shaft divided by the amount of energy delivered to the system [4,5]. Fig. 5 shows that the biodiesel blends BTE at 25% engine load are higher than that of D100. At higher loads (from 50%, 75% and 100%), D100 has consistently higher BTE than other biodiesel blends, except D80WCO20 at 100% load, which is almost the same. The higher viscosity and density of the biodiesels and the lower cetane number of the microalgal biodiesel compared to petroleum diesel could induce a higher ignition delay and higher fuel consumption, and therefore reduce the BTE for biodiesel at higher engine loads [5].

3.4. Impact of biodiesel blends on heat release rate

The heat release rate is another important parameter for evaluating combustion characteristics of a fuel. Fig. 6(a–d) shows the effect of the crank angle on the heat release rate of a test engine operated on D100 and the biodiesel blends (D90A10, D80A20, D50A50 and D80WCO20), at 25%, 50%, 75% and 100% engine loads. At 25% load, petroleum diesel had a higher heat release rate

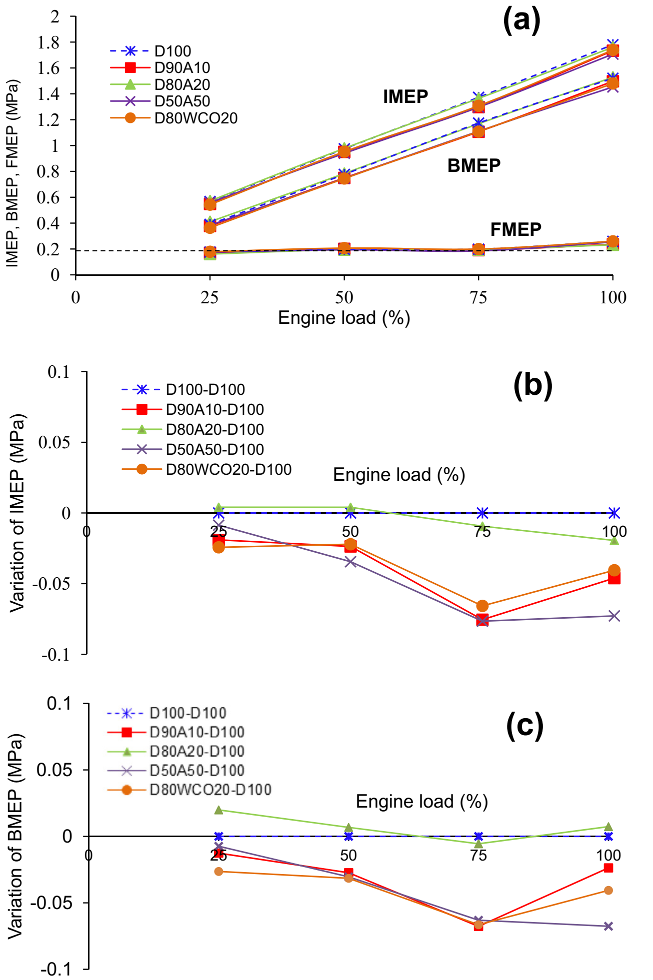


Fig. 4. Effect of engine load on the indicated mean effective pressure (IMEP), brake mean effective pressure (BMEP) and frictional mean effective pressure (FMEP) (a) and their variation (b and c) for petroleum diesel and biodiesel blends.

(Fig. 6a). This can be explained by the higher viscosities of biodiesel at lower load, leading to incomplete combustion. A similar conclusion was drawn by [22]. Furthermore, the lower calorific value of biodiesel is also a factor in reducing the heat release rate, as reported in [5]. However, at 50% and 75% load, the peak heat release rate of all biodiesel blends was almost comparable to that of D100. At full load, D80WCO20 had a higher peak heat release rate than D100. This is associated with the higher BTE of D80WCO20, likely caused by a change in the combustion regime at full load. In addition, the injection system is incorporated with the pilot injection, which helps to improve combustion performance and thermal efficiency [13]. There are small peaks in the heat release rate shown in Fig. 6(b, c, and d) at around 12, 15 and 18 degrees respectively, before TDC (top dead centre). This peak is due to the pilot injection to the system and it is clear that at higher load, microalgae methyl ester blends have little delay in combustion, when compared with waste cooking oil methyl ester D80WCO20 and petroleum diesel D100.

3.5. Impact of biodiesel blends on nitric oxide (NO) and nitrogen oxide (NOx) emission

Formation of NO_x depends on in-cylinder temperature, ignition delay and oxygen content in the fuel [2,12]. Longer chain length and higher amounts of unsaturated fatty acids in biodiesel have been reported to correlate with increases in NO_x emissions [41]. The correlations between NO and NO_x emissions and brake mean effective pressure for the fuels used in this study are shown in Fig. 7(a) and (b). NO and NO_x emissions increased for microalgae biodiesel blends compared to D100 at all load conditions, except for D90A10. Despite differences in amounts of unsaturation and fatty acid chain lengths, the similar blend ratios of microalgae biodiesel blend D80A20 and waste cooking oil methyl ester blend D80WCO20 were also similar in NO and NO_x emissions.

Fig. 7(a) shows that NO emission of biodiesel D80A20 and D80WCO20 increased around 5% at lower BMEP and 10% at maximum BMEP compared with that of D100. NO emissions were 14% higher for D50A50 at 25% load, compared to D100, which increased to 26% at full load. Similar trends were observed for NO_x emissions (Fig. 7b). Both increase and decrease of NO_x emissions for various biodiesels and their blends have been reported [3,21,10,30,31], with most studies showing increased NO_x emissions from biodiesels.

Thermal NO_x formation of biodiesels could be the result of lower cetane numbers increasing ignition delay, resulting in an increased rate of premixed combustion and peak heat release [8,39]. In addition, adiabatic flame temperature increases with the increase in biodiesel carbon chain length, also favouring NO_x

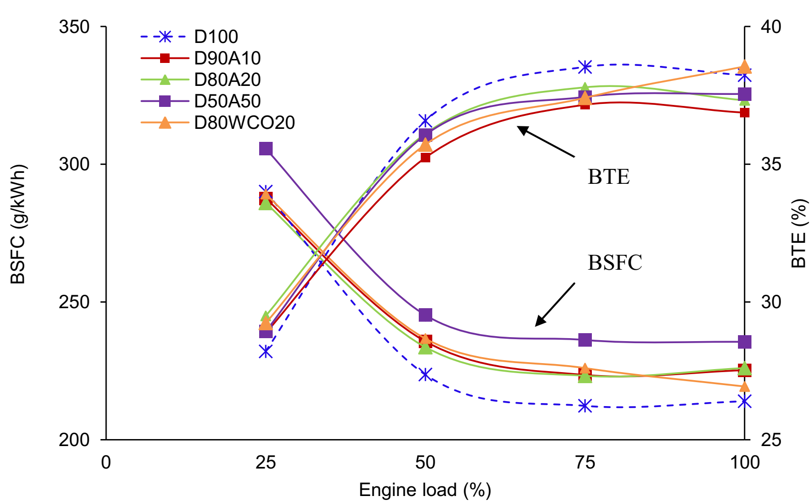


Fig. 5. Variation of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) with engine load for petroleum diesel and biodiesel blends.

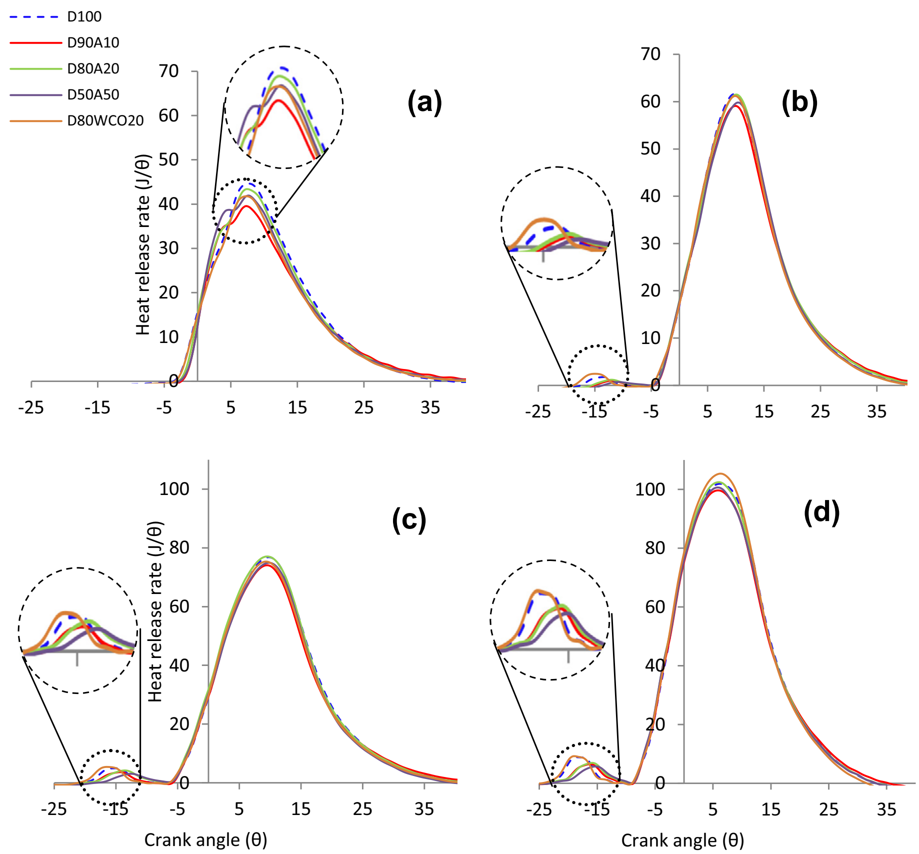


Fig. 6. Effect of crank angle on the heat release rate at (a) 25%, (b) 50%, (c) 75% and (d) 100% of engine load operated on petroleum diesel and biodiesel blends.

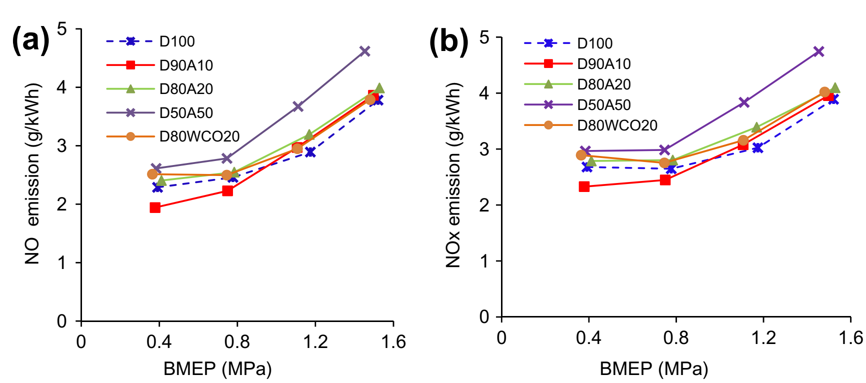


Fig. 7. Correlation between exhaust emission (a) nitric oxide NO (b) nitrogen oxide NO_x and brake mean effective pressure (BMEP) for petroleum diesel and biodiesel blends.

formation [39]. Furthermore, biodiesels contain oxygen, which improves combustion and subsequently raises the in-cylinder temperature, thereby enhancing NO_x formation [2,12,5]. In Fig. 7(a) and (b) the NO_x emission of D80A20 and D80WCO20 is almost similar in all BMEP with a small increase compared to that of D100. However, D90A10 has a lower NO_x emission than that of D100 at low BMEPs and is comparable at higher BMEPs. These results suggest thata relatively low cetane number, longer carbon chain length and the oxygen content of microalgae biodiesel could be responsible, for there are higher NO_x emissions than the reference petroleum diesel only when biomass-derived FAME content is beyond a threshold >20% blends.

3.6. Impact of biodiesel blends on unburned hydrocarbon (UHC) emission

An inability to reach the ignition temperature of fuel to be oxidised or a lack of oxygen have been reported for the presence of UHC in the exhaust gases [37]. The oxygen content in biodiesel has been shown to pre-oxidise the air fuel mixture leading to a reduction of UHC emissions [7]. Furthermore, an inverse correlation between chain length and UHC emissions has been demonstrated [28]. UHC emissions of tested microalgae methyl ester/petroleum diesel blends were significantly lower, compared to petroleum diesel D100 and D80WCO20, as shown in Fig. 8. At

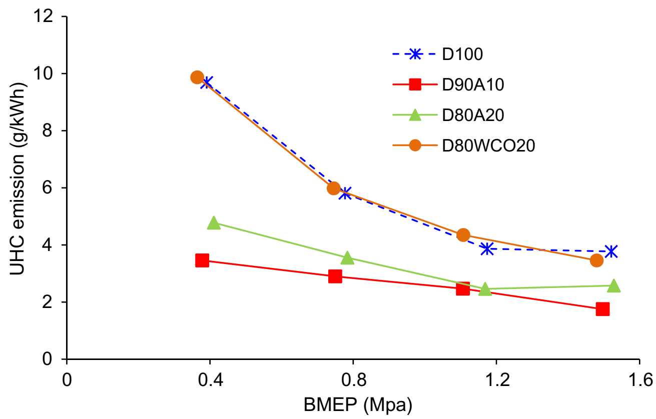


Fig. 8. Correlation between unburned hydrocarbon (UHC) emission and brake mean effective pressure for a test engine operated with petroleum diesel and biodiesel blends.

low BMEP, UHC emissions of D90A10 were 64% lower compared to D100. At maximum BMEP, a 47% reduction in UHC emissions was observed. Due to experimental error, D50A50 blend data are missing in this analysis. On the other hand, UHC emission profiles of the waste cooking oil methyl ester/petroleum diesel blend D80WCO20 followed almost the same trend as petroleum diesel D100. The ~68% content of very long chain fatty acids 22:5 and 22:6 (DHA) of the microalgae methyl ester could be a possible explanation for the observed lower UHC emissions of the microalgal biodiesel blends, however, the higher UHC emissions of the 20% blend compared to the 10% blend is inconsistent with this explanation. Likewise, oxygen content is an unreasonable explanation for the same reason and more importantly because of the almost identical UHC emissions of the D80WCO20 blend, compared to D100.

4. Conclusion

In this experimental study, microalgae biodiesel blends were used in a modern diesel engine and compared with another biodiesel blend, made from waste cooking oil and petroleum diesel. The following major conclusions can be drawn.

The physical and chemical properties of microalgae fatty acid methyl esters (microalgae biodiesel (B100)) were within biodiesel standards ASTM 6751-12 and EN 14214, except for the cetane number and density. However, the performance of the microalgae oil methyl ester is comparable with other microalgae oil methyl esters with fuel properties within the biofuel standard.

Microalgae methyl ester blends generate slightly lower cylinder pressures when compared with petroleum diesel, and pressure rise rate was increased. The indicated mean effective pressure and brake mean effective pressure were also slightly reduced with the microalgae methyl ester/petroleum diesel blends, especially at 75% engine load, potentially due to lower calorific value and higher viscosity, but frictional losses were reduced potentially due to higher viscosity of the blends.

The brake-specific fuel consumption of microalgae biodiesel methyl ester blend D50A50 increased 9.3%, compared to that of D100. This reduction is due to the 11% less calorific value of pure microalgae methyl ester than petroleum diesel. Due to higher fuel consumption, the brake thermal efficiency of all biodiesel blends was reduced.

The heat release rate represents the net energy released as heat during combustion. As such, it is a critical parameter to evaluate the suitability of a fuel for use in an internal combustion engine. Most of the tested biodiesel blends were not significantly different to petroleum diesel. An exception was the waste cooking oil blend, which was slightly higher at full load

Biodiesel blends have significant variations compared to petroleum diesel with regard to gaseous emissions. Increases in NO, and NO_x emissions compared to petroleum diesel were observed for all biodiesel blends. However, UHC emissions were greatly reduced for microalgae biodiesel blends, whereas 20% waste cooking oil methyl ester/petroleum diesel blends followed the same UHC emission trends as petroleum diesel.

The data suggest that despite the highly unsuitable fatty acid profile of the source organism, *C. cohnii*, a 20% microalgal biodiesel blend (D80A20) had the closest alignment in performance to petroleum diesel D100.

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