

Article

***Chlorella protothecoides* Microalgae as an Alternative Fuel for Tractor Diesel Engines**

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Abstract: Biodiesel has attracted a great deal attention recently as an alternative fuel due to increasing fuel prices and the imperative to reduce emissions. Among a wide range of biodiesel resources, microalgae are a promising alternative fuel source because of the high biomass, lipid productivity and environmentally friendliness. Microalgae is also a non-edible food, therefore, there will be no impact on the human food supply chain. In this work, petroleum diesel (PD) and biodiesel from the microalgae *Chlorella protothecoides* (MCP-B20) blend have been used to examine the performance and the emission of a 25.8 kW agriculture tractor engine. Two engine speeds at maximum power take off (PTO) power and torque have been selected for analysis using analysis of variance (ANOVA). The results showed that there is no significant difference between the engine performance when microalgae biodiesel blend (MCP-B20) and PD were used. However, a significant reduction in CO, CO₂ and NO emissions was found when MCP-B20 was used. These outcomes give strong indication that microalgae can be successfully used in tractors as alternative fuel.

Keywords: microalgae; diesel; biodiesel; tractor performance; emissions

Abbreviations

PD	Petroleum Diesel
MCP	Microalgae <i>Chlorella Protothecoides</i>
MCP-B20	Microalgae <i>Chlorella Protothecoides</i> Biodiesel blend of 20% with 80% PD
MCP-B100	Microalgae <i>Chlorella Protothecoides</i> Biodiesel 100%
MCP-O	Microalgae <i>Chlorella Protothecoides</i> oil
PTO	Power Take Off
ANOVA	Analysis Of Variance
WOT	Wide Open Throttle
HOT	Half Open Throttle
db	Decibel
FAMES	Fatty Acid Methyl Esters
BSFC	Brake Specific Fuel Consumption
GIP	Gross Input Power
UTHC	Unburnt Total Hydrocarbon
PM	Particulate matter

1. Introduction

The increased demand on energy associated with fossil fuel has resulted in problems such as high prices, supply depletion and emissions, which in recent years have been the main factors encouraging an increased focus on alternative fuels. Enhancing energy security is another factor for pushing toward alternative fuels to vary the sources of energy and reduce the demand on importing oil. Dyer & Farm tractors and other agricultural machinery consume a significant amount of fuel and contribute to the gas emissions which cause global warming. Biodiesel is regarded as one of the best alternative fuels for diesel engines [1,2]. Biodiesel is renewable, environmentally friendly, non-toxic, biodegradable and does not require significant modification to existing technology [3]. Biodiesel is the product of reacting triglycerides with an alcohol in the presence of an acid or base catalyst to form a fatty acid ester and glycerol. The process of converting vegetable oil or animal fat to biodiesel is called transesterification [4–7]. Transesterification has been widely used in biodiesel production to enhance the fuel properties and reduce the viscosity [5,8]. However, using biodiesel as a source of energy can lead to a rise in food prices. At the same time biodiesel availability cannot cover even current transportation fuel demand [9]. The main sectors that consume conventional liquid fuel are transport and agriculture and by 2011–2012 the worldwide demand for diesel fuel will be some 66.90 million tonnes with the anticipated increased consumption in the agricultural sector [10]. Among different biodiesel feedstocks, microalgae were reported as a potential future fuel. Microalgae are microorganisms which have the ability to convert CO₂ and sunlight into useful oil. The oil productivity of microalgae is much greater than that of crop oils. In the same way microalgae have the ability to grow under such conditions that the effect on agriculture is insignificant. The topic of biodiesel production from microalgae has received a great deal of attention recently because it is renewable, environmentally friendly and has the ability to convert CO₂ to oil feedstock for biodiesel production. Microalgae biofuel is non-toxic, contains no sulphur and is highly bio-degradable. After extracting the

oil, the leftover material can be used as soil fertilizer or used in ethanol production [4]. Microalgae have high biomass and lipid productivity per unit of area in comparison with crops [11]. Chisti [9] reported that the demand for transportation fuel can only be covered by microalgae as a renewable source. The same amount of biodiesel from microalgae (for 30% w/w oil content) compared to rapeseed or soybean crops requires less land, around 49 to 132 times [12]. Furthermore, microalgae are non-edible and can grow under various conditions in which there is no significant effect of human food supplies [13,14]. One of the major arguments against the production of biodiesel from agricultural crops is that it will result in food shortages and raise food prices. However, the production of biodiesel from microalgae circumvents these arguments. *Chlorella* species' benefits include fast growth and easy cultivation, which make it an attractive potential energy source, however, it is not commercially viable due to its low lipid content [15]. Haik *et al.* [16] conducted research studies to understand the effect of using algae fuel on the combustion quality, in-cylinder pressure and heat released. Haik *et al.* [16] reported that algae oil methyl ester properties are similar to those of diesel, and thus they used algae fuel (both algae oil and algae oil methyl ester) successfully in a single cylinder Ricardo engine. The combustion results demonstrated that algae methyl ester produced a marginally higher heat release rate in comparison to diesel. The heat increment can be attributed to the longer combustion delay period of algae fuel in comparison to diesel. However in the case of algae oil, it was found there is a noticeable reduction in both in-cylinder pressure and heat released compared to diesel. This reduction can be attributed to the difference in the properties of algae oil and algae oil methyl ester. A similar outcome was concluded by our research team (results were not reported here).

In agricultural work, tractors are the major power source in the agricultural field and one of the main fuel consumers in the biodiesel production chain. Dorado *et al.* [2] tested biodiesel from olive waste cooking oil in a direct-injection engine (Perkins, model AD 3-152A) and satisfactory performance and no statistically significant differences were achieved throughout the test using biodiesel and diesel fuel. However; up to a 26% increase in the brake-specific fuel consumption and less than 8% of the power loss were pointed out in comparison with diesel. Matthew [17] used a diesel tractor (John Deere 3203, John Deere, Moline, IL, USA) to test the performance and emissions when using No. 2 diesel (D2), 20% biodiesel (B20), and 100% biodiesel (B100). The test focused on the variation in specific fuel consumption, power take-off (PTO) torque, PTO power, thermal efficiency and NO_x emissions between those different fuels. The results showed that there are no statistically significant differences between diesel and B20. Neel *et al.* [18] used a 23.9 kW compact utility tractor (John Deere 3203) to compare the PTO power performance, fuel efficiency, and NO_x using petroleum diesel, biodiesel blend (B20), and neat biodiesel (B100) at rated PTO speed (540 RPM) and at peak torque load conditions. The results showed that when the tractor was fuelled by D2 or B20, similar performance was found at peak torque. Biodiesel B20 was recommended by [19] as the optimal biodiesel blend due the similar performance to diesel.

In this work, tractor PTO tests were conducted to evaluate the tractor engine performance and emissions using petroleum diesel (PD) and microalgae biodiesel (MCP-B20) under different tractor operation conditions. The performance and the emission map have been drawn for wide open "throttle" (WOT) and half open "throttle" (HOT). Further analyses were conducted using SPSS analytics software for the PTO rated speed and peak power during the WOT test. The analysis of

variance (ANOVA) was used to identify the significant differences between the means values of the two fuels at the selected speeds.

2. Methods

2.1. Experimental Tractor and Apparatus

A stationary PTO test has been conducted in the agricultural equipment laboratory at the University of Southern Queensland. The test aims to study the performance and emissions of a farm tractor fuelled with 20% *Chlorella protothecoides* microalgae biodiesel blend (MCP-B20). The experimental results were used for comparison with petroleum diesel (PD). The tractor used in the experiment was a John Deere 4410 e-hydro, as shown in Figure 1. The engine in the JD4410 tractor is a Yanmar 3TNE88, three cylinder water cooled diesel engine with 18.8:1 compression ratio. The engine power is 25.8 kW and the manufacture's estimated PTO power is 21.3 kW. The engine torque at rated speed is 87.9 Nm.

Figure 1. The experiment setup: (1) the tractor; (2) fuel system; (3) gas analyzer; (4) dynamometer; (5) PTO connecting road.



In order to apply load on the tractor engine, a PTO dynamometer was used (Figure 1, items 4 and 5). The dynamometer was modified by adding a load cell and digital monitor to measure PTO speed (RPM) and torque (Nm) to calculate the power (kW). The dynamometer was calibrated prior to the tests using five standard weights of 20 kg each. The calibration started by running the monitor of the dynamometer in the calibration mode. Then the zero torque was set. Standard weights of 100 kg were suspended on a one meter arm to apply load on the load cell. At that time the torque of 981 Nm was set on the screen. An optical tachometer was used to check the PTO speed. The ratio of the engine to the PTO speeds was found to be 4.815. The level of accuracy of this load cell is around $\pm 2.5\%$.

A BEA 460 Bosch gas analyser was used to monitor the tractor exhaust gases for O₂, CO, CO₂, NO and Lambda. The gas analyser was connected to a laptop to record and save the data (Figure 1, item 3). The operating ranges (sensitivity) and resolutions are shown in Table 1. Prior to the test, the device was subjected to maintenance and calibration by the manufacturer and daily standard calibration.

Table 1. The gas analyser ranges, accuracy and resolution.

Component	Min.	Max.	Resolution
CO (%vol)	0	10.00	0.001
CO ₂ (%vol)	0	18.00	0.01
Lambda	0.5	22.00	0.001
NO (PPM)	0	5000	1

To compare the noise level produced from the tractor engine using the different fuels, a Larson Davis SoundTrack™ LxT Sound Level Meter was placed at the operator head position.

2.2. Test Fuels and Procedure

Chlorella protothecoides microalgae oil (100%, MCP-O) was obtained from Soley Institute Turkey. The MCP-O was converted to biodiesel through transesterification. The transesterification procedure was conducted by heating the oil to 48°C. For one litre of MCP-O, an amount of 9 g of NaOH was added to 220 mL of methanol and mixed. The mixture was added to the oil and mixed for 40 minutes. After 10 hours, the oil phase was separated to another flask and centrifuged to remove the glycerin produced. The biodiesel was then washed with 500 mL of water. After one hour, another washing with 500 mL of water was conducted. The mixture of biodiesel and water was centrifuged to remove all the remaining water from the biodiesel. Table 2 represents the properties of the fuels used in this test PD and MCP-B100. The chemical formula of MCP-B100 is $C_{18.151}H_{34.376}O_{1.942}$ as reported by [20,21]. To prepare the MCP-B20 blend, 20% by volume of MCP-B100 was mixed with 80% by volume of PD. The specification of MCP-B20 was calculated from the PD and MCP-B20 depending on their volume in the blend. MCP-B20 have higher cetane number comes from the high percentage of unsaturated FAMES.

The fuel consumption rate was measured using the measuring cylinder shown in Figure 2. Initially a digital flowmeter was used to measure the mass flow rate of diesel; however the data fluctuated. Thus, a volumetric cylinder was successfully and accurately used in this research work [22]. The measuring cylinder was fitted with a two-way valve at both the top and bottom. The top two-way valve allowed for the fuel returning from the injectors to either enter the cylinder or return to the tank. The bottom two-way valve allowed for the fuel to either be drawn from the cylinder or to be supplied from the tank. In order to obtain a fuel consumption reading, the top and bottom valve were opened simultaneously allowing return fuel to enter the cylinder whilst fuel was being drawn from the bottom.

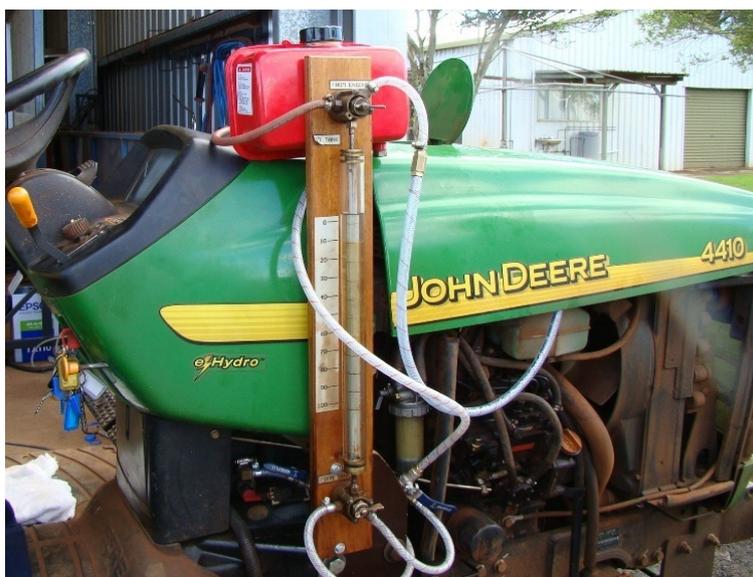
A separate tank was connected while MCP-B20 fuel was being used. The time was recorded using a stop watch for the fixed volume of fuel consumed. The fuel consumption measurements were repeated three times at each speed to reduce the error. At the end of the test using PD, the system was cleaned and the fuel filter was changed to prevent any contamination from the previous test.

In this work the tractor test results of the comparison between PD and MCP-B20 were presented using the WOT and HOT tests. At WOT the engine speed was fixed at 2700 RPM (PTO speed 550 RPM) at no load using a fuel controller. Then the load was applied on the tractor until a fix reduction in speed was achieved. Subsequently, PTO and engine speed, torque and power, fuel consumption, exhaust gas temperature, noise level and exhaust gas emission were monitored.

Table 2. Fuel properties [20].

Fuel property	Petroleum diesel (PD)	MCP-B100 [21]	MCP-B20
Cetane Number	49	52	49.6
Calorific Value (MJ/kg)	46	40.04*	44.8*
Density at 15 °C (kg/L)	0.83	0.867	0.8374
Viscosity at 40 °C (cp)	2.525*	2.8*	4.22*
Flash point (°C)	79	124	88
Carbon residue % (m/m)	-	0.2	-
Total contamination (mg/kg)	-	2	-
Oxidation stability, 110 °C hours	-	12	-
Acid value (mg KOH/g)	<0.1	0.3	0.14
Iodine value	-	47	-
Sulfated ash content (%)	-	0.01	-
Water content (mg/kg)	-	80	-
Methanol content (%)	-	0.04	-
Sulfuret content (mg/kg)	8	2	6.8
Phosphorus content (mg/kg)	-	3	-
Linolenic acid methyl ester (%)	-	2	-
Monoglyceride content (%)	-	0.2	-
Diglyceride content (%)	-	0.04	-
Triglyceride content (%)	-	0.02	-
Free glycerol (%)	-	0.008	-
Total glycerol (%)	-	0.02	-

* Measured by the authors.

Figure 2. Fuel consumption measurement system.

The same procedure was followed for the HOT test, however, the engine speed without load was fixed on 2000 RPM (PTO speed about 415 RPM). In each test, the tractor engine was warmed up for 30 minutes using PD fuel. In order to have consistent readings, the tests were conducted under the same atmospheric conditions where humidity, atmospheric pressure and temperatures are relatively

constant. The dynamometer was carefully calibrated prior to the tests. Each test was repeated three to five times and average data was used and reported in this work.

3. Results and Discussion

3.1. Statistical Analysis

Tables 3 and 4 show the descriptive statistical and ANOVA tests for the tractor test at WOT for two speeds from the performance experiment. The first (point) speed was rated PTO speed 540 RPM (engine speed 2600 RPM). The second (point) speed was at peak PTO torque (engine speed 1500 RPM). In these tables, the F values show the (statistically) significant differences between PD and MCP-B20 fuel for all the parameters in this study.

Table 3. Descriptive statistics and ANOVA summary for tractor engine performance and emissions at WOT, rated PTO speed 540 RPM (engine speed 2600 RPM).

Variable	PD		MCP-B20		ANOVA F
	M	SD	M	SD	
Engine Torque (Nm)	38.205	1.246	35.37	0.65	16.246***
PTO Torque (Nm)	220.25	7.182	203.9	3.747	16.294***
Gross input power	55.347	2.34	50.3	1.949	10.951**
Engine Power (kW)	10.395	0.337	9.627	0.178	16.206***
PTO Power (kW)	12.232	0.399	11.327	0.209	16.129***
BSFC (kg/kWh)	451.645	31.642	453.735	25.47	0.011
Engine efficiency (%)	18.825	1.374	19.162	1.08	0.149
Noise level (db)	90.9	0.408	90.375	0.33	3.997
Exhaust temperature (°C)	356	4.082	350	4.32	4.075
CO ₂ (%)	7.97	0.049	7.375	0.15	56.720***
CO (%)	0.036	0.006	0.250	0.005	7.188***
O ₂ (%)	9.58	0.258	10.53	0.294	23.543***
NO (PPM)	541.5	20.68	493.5	22.22	10.003**
Lambda	1.835	0.034	2.016	0.0325	59.114***

** The difference is significant at $p < 0.01$; *** The difference is significant at $p < 0.001$.

Table 4. Descriptive statistics and ANOVA summary for tractor engine performance and emissions at WOT, peak PTO torque (1500 RPM).

Variable	PD		MCP-B20		ANOVA F
	M	SD	M	SD	
Engine Torque (Nm)	79.1025	0.587	78.235	0.585	4.38
PTO Torque (Nm)	456	3.366	451	3.35	4.412
Gross input power (kW)	50.937	3.118	50.882	2.578	0.001
Engine Power (kW)	12.42	0.092	12.28	0.09	4.292
PTO Power (kW)	14.6	0.106	14.450	0.109	4.297
BSFC (kg/kWh)	347.547	23.798	359.35	17.559	0.637
Engine efficiency (%)	24.454	1.589	24.184	1.158	0.076
Noise level (db)	86.3	0.622	85.9	0.648	0.793

Table 4. Cont.

Variable	PD		MCP-B20		ANOVA F
	M	SD	M	SD	
Exhaust temperature (°C)	470	5.77	480	5.788	5.985*
CO ₂ (%)	12.105	0.0914	12.025	0.881	1.587
CO (%)	0.902	0.015	0.85	0.008	37.8***
O ₂ (%)	2.98	0.077	3.102	0.074	5.254
NO (PPM)	970	5.715	994	3.651	50.087***
Lambda	1.13	0.008	1.14	0.016	1.2

* The difference is significant at $p < 0.05$; *** The difference is significant at $p < 0.001$.

3.2. Tractor Engine Performance

In this work, the tractor PTO test was conducted to evaluate and compare the tractor engine performance using PD and MCP-B20 at WOT and HOT. The input power (IP), torque, brake power (BP), brake specific fuel consumption (BSFC), noise level and exhaust temperature are presented in the following sections.

3.2.1. Tractor Engine Gross Input Power (kW) and Tractor Engine Brake Power (kW)

Figures 3 and 4 show the relationship between the tractor engine speeds and the engine gross input power (GIP) and engine brake power (BP) using PD and MCP-B20 for the WOT and HOT tests. The GIP power is the result of lower calorific value multiplied by the fuel flow rate. From Figures 3 and 4, it can be seen that the maximum GIP take place at the engine speed of around 2500 RPM for both fuels at WOT. The maximums GIP are 75.9 and 73.1 kW and the maximums for BP are 15.8 kW for PD and MCP-B20 respectively. Table 3, Figures 3 and 4 show that at the rated PTO speed (2600 RPM engine speed) there are significant reductions in GIP 5.1 kW and BP 0.77 kW when the tractor is fuelled by MCP-B20 in comparison to PD. This reduction is due to the difference in heating value between microalgae fuel and diesel. This finding agrees with Neel *et al.* [18] and disagrees with Kulkarni *et al.* [19] who found a significant difference and insignificant difference, respectively, between tractor PTO power between PD and B20 biodiesel at rated PTO speeds. There is no significant difference that can be seen in Table 4 at the point of maximum PTO torque between PD and MCP-B20, which agrees with the insignificant difference found between PD and B20 biodiesel at typical pumping speed and peak PTO torque in Kulkarni *et al.* [19] and Neel *et al.* [18] respectively. A similar trend is found for the HOT and WOT test, however the MCP-B20 shows higher GIP and BP at 1,800 RPM. These findings associated with results in Table 4 and Figures 3 and 4 show that the differences between the PD and MCP-B20 for the general case are not significant. The close results between PD and MCP-B20 are due to the higher density for MCP-B20 which reduces the effect of the reduction in the lower calorific value for MCP-B20 than PD.

Figure 3. The relationship between tractor engine speeds (RPM) and engine gross input power (kW) for PD and MCP-B20.

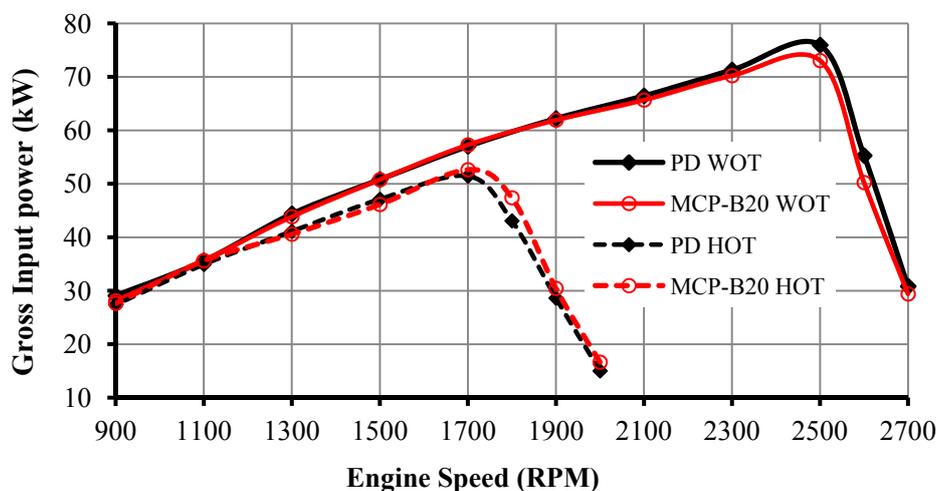
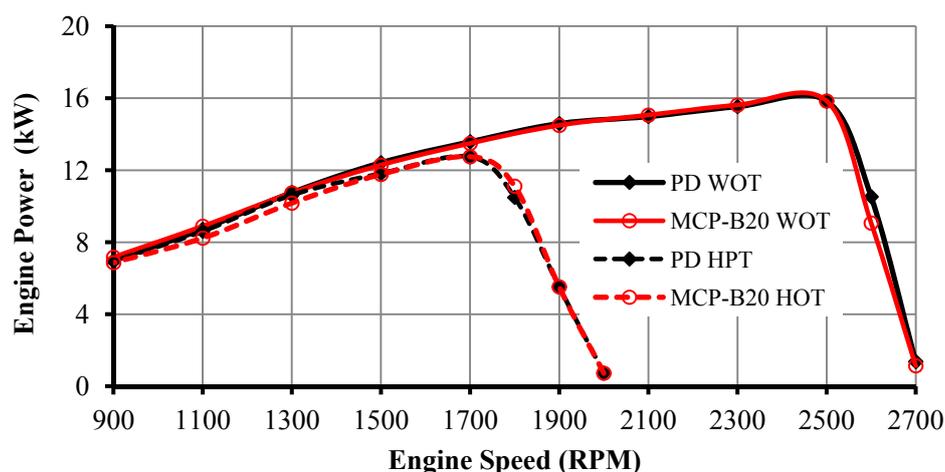


Figure 4. The relationship between tractor engine speeds (RPM) and engine power (kW) for PD and MCP-B20.



3.2.2. Tractor Engine Torque (Nm) and Engine Efficiency (%)

Figure 5 presents the tractor engine torque for the WOT and HOT tests against the tractor engine speeds. The maximum tractor engine torques are found at engine speeds between 1300 RPM and 1500 RPM for both fuels. The maximum difference between the PD and MCP-B20 for the WOT test of 5.4 Nm occurs at rated PTO speed (2600 RPM engine speed). The ANOVA test for this point in Table 3 showed that there is a significant different in tractor engine torque between the two fuels. This finding agrees with Neel *et al.*'s [18] results for PTO torque between PD and B20 fuel. However Kulkarni, *et al.* [19] found no significant difference in the engine torque between PD and B20 fuel. At the peak torque point, and all points in Figure 5, the results show comparable outcomes in the WOT test. These results agree with Kulkarni *et al.*'s [19] and Neel *et al.*'s [18] findings at 1,800 RPM and the peak torque results, respectively. The HOT test shows that when the tractor is fuelled by MCP-B20, both a reduction and increment can be found when compared with PD.

Figure 5. The relationship between tractor engine speeds (RPM) and engine torque (Nm) for PD and MCP-B20.

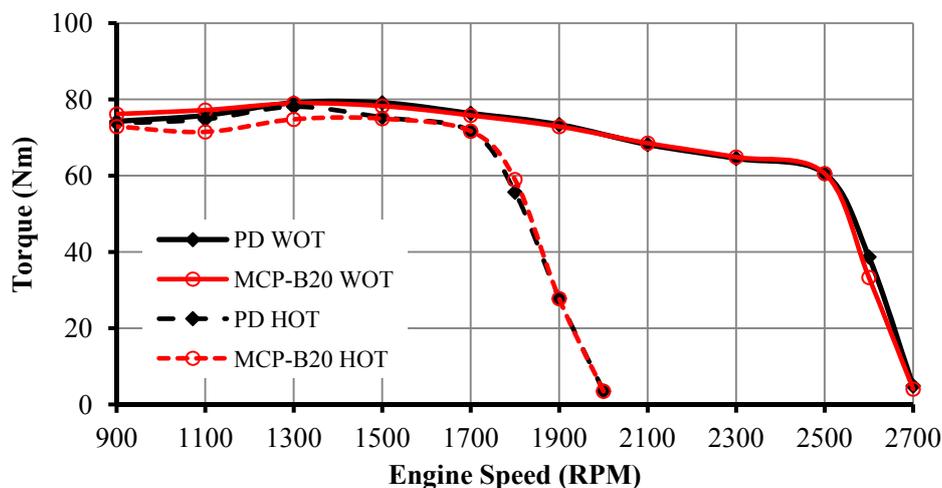
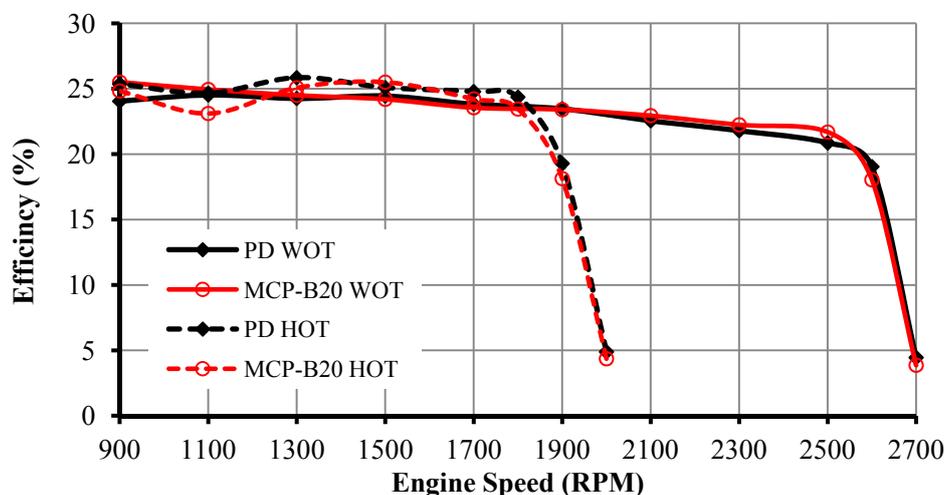


Figure 6 shows that the engine efficiency decreases when engine speeds increase for both fuels. The higher engine efficiency at low engine speeds comes from high load applied which reduced engine speed. This reduction comes from low heat losses at high load [23].

Figure 6. The relationship between tractor engine speeds (RPM) and engine efficiency (%) for PD and MCP-B20.

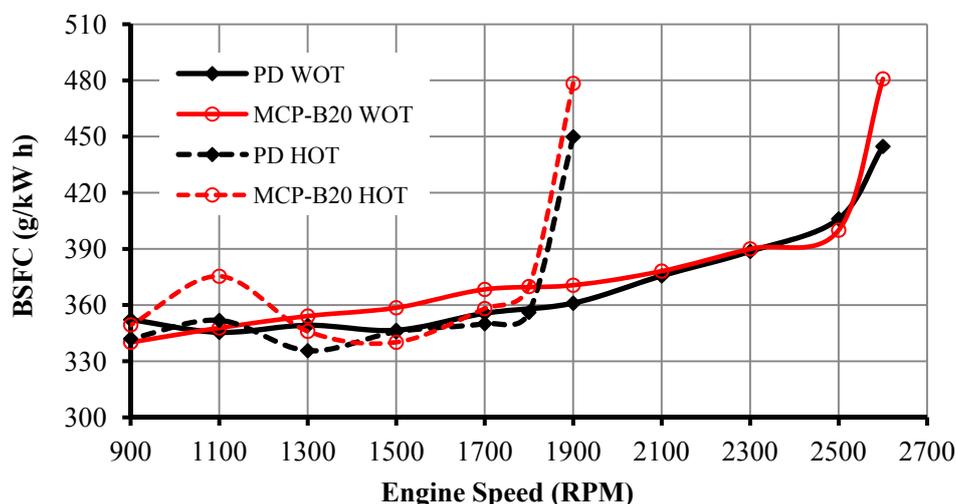


The HOT test shows that MCP-B20 excels in giving higher engine efficiency for the speeds below 1700 RPM. The higher efficiency for MCP-B20 comes from the lower IP in spite of the slightly lower BP to PD. That is related to the better combustion that comes from the extra oxygen in biodiesel [24]. Tables 3 and 4 illustrate that there are no significant differences in tractor engine efficiency between PD and MCP-B20 at the rated PTO speed and for the peak torque. This is in agreement with the finding of Kulkarni *et al.* [19] and Neel *et al.* [18] as they found no significant differences in thermal efficiency at rated speed, pumping and peak torque between PD and B20 biodiesel.

3.2.3. Brake Specific Fuel Consumption (BSFC)

The BSFC was calculated by dividing the fuel consumption rate by the BP. Figure 7 illustrates the relationship between the tractor engine speeds (RPM) and engine BSFC (g/kWh) for PD and MCP-B20. However this figure shows an increase in the BSFC when the tractor is fueled by MCP-B20 than the PD at most engine speeds except at 2500 RPM and 900 RPM for the WOT test, lower BSFC is found at 1500 RPM for the HOT test. Statistically, Table 3 and Table 4 show that there are no significant differences in BSFC between the two fuels at rated PTO speed and at the peak torque points. That is due to the high SD found at this parameter. The increase in BSFC is understandable due to the lower calorific values of MCP-B20 compared with that of mineral diesel. However, the density of MPC-20 is higher than that of diesel.

Figure 7. The relationship between tractor engine speeds (RPM) and engine BSFC (g/kWh) for PD and MCP-B20.



3.2.4. Exhaust Temperature (°C) and Tractor Noise Level (db)

Figure 8 shows the tractor exhaust temperatures (°C) against the tractor engine speeds (RPM) for PD and MCP-B20. From the WOT and HOT tests it can be seen that the exhaust temperatures increase when the engine speed increases until reaching the maximum, then the temperatures decline. The maximum exhaust temperatures for the WOT test for both fuels are between the engine speeds of 1700 RPM to 2500 RPM, while for the HOT test the maximum exhaust temperatures are found at the engine speeds between 1300 RPM to 1700 RPM. Tables 3 and 4 show that there are no significant differences between the two fuels at the rated PTO speed and peak torque points in tractor exhaust temperatures. The maximum difference between the two fuels of 59°C is found at 1300 RPM for the WOT test.

The relationship between tractor engine speeds (RPM) and noise level (db) measured at the tractor operator head position for PD and MCP-B20 are presented in Figure 9 at WOT and HOT. The noise level in this figure mostly originates from the tractor engine. However, there is considerable noise that comes from the PTO dynamometer and its shaft which couldn't be avoided during the test. That makes the noise level at all speeds considerably high.

Figure 8. The relationship between tractor engine speeds (RPM) and exhaust temperature ($^{\circ}\text{C}$) for PD and MCP-B20.

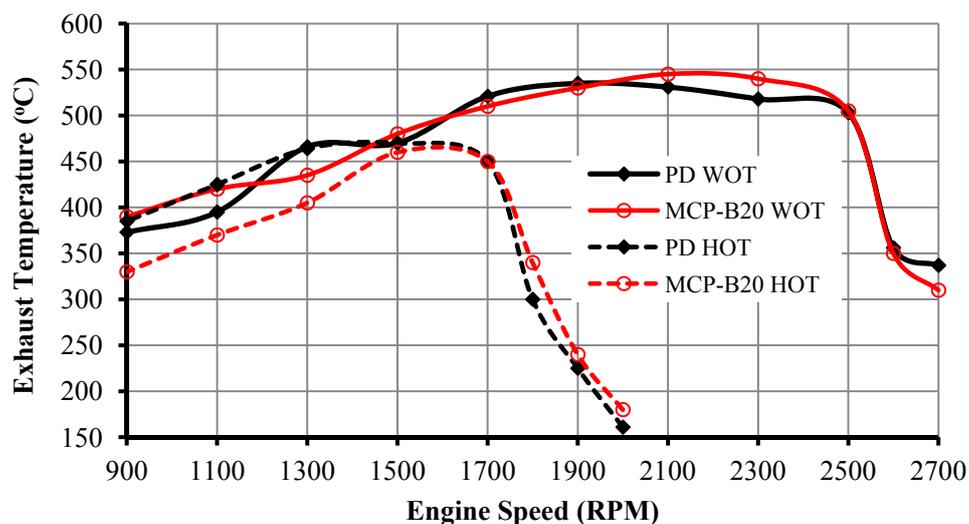
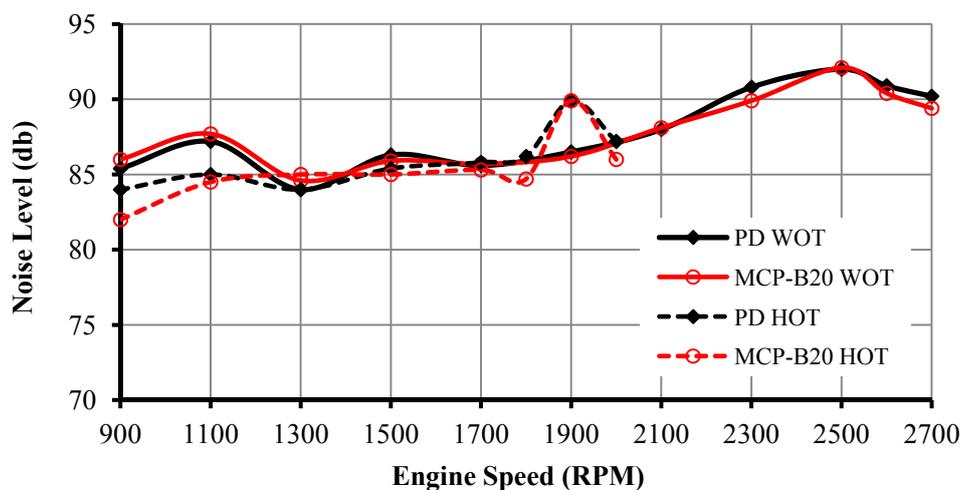


Figure 9. The relationship between tractor engine speeds (RPM) and noise level (db) for PD and MCP-B20.



The noise coming from the dynamometer is not constant at all engine speeds, it is affected by tractor vibration which is the main cause for high levels of noise at the speeds of 2500 RPM and 1100 RPM for the WOT test as well as 1900 RPM for the HOT test. At these speeds the tractor vibration is significantly greater than at other speeds. The noise caused by the tractor vibration that contributes to the tractor noise is insignificant when fueled by PD and MCP-B20 as revealed in Tables 3 and 4. The peak noise occurs at the engine speed 2500 RPM for both fuels. At this point there is a considerable load associated with high engine speed that result in the highest noises of about 92 db and 92.1 db for PD and MCP-B20 respectively for the WOT test.

3.3. Tractor Engine Emissions

3.3.1. Carbon Monoxide (CO) and Carbon Dioxide (CO₂)

The comparison of CO emissions from PD and MCP-B20 in Figure 10 shows that MCP-B20 produced a significantly less CO% than PD at most points in the WOT test and at most the engine speeds in the HOT test except 1800 RPM, at which MCP-B20 gives a slightly higher CO%. This result is in a good agreement with the Nabi *et al.* [1] conclusion that biodiesel from cotton seed oil produces less CO than net diesel. Less CO is an indication of better combustion in MCP-B20 than PD which comes from the extra oxygen in the biodiesel form. This significant reduction in CO% is confirmed by ANOVA in Table 3 and Table 4 that show a significantly high reduction in CO% produced from the tractor engine when fuelled by MCP-B20 compared to PD at the rated PTO speed and peak torque. The maximum differences between the concentration of CO are clearly noticeable at the lower engine speeds ranging between 1300 RPM and 1100 RPM for both the WOT and HOT tests, and these results agree Yusaf *et al.* [25], however, there is a disagreement with the higher results found in CO PPM produced from the engine fuelled by B25 of crude palm oil biodiesel when compared with diesel fuel.

Figure 10. The relationship between tractor engine speeds (RPM) and CO (%) for PD and MCP-B20.

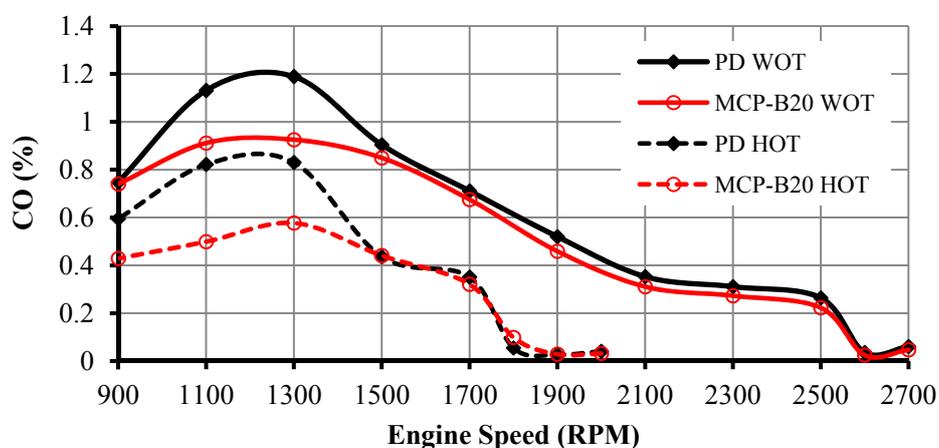
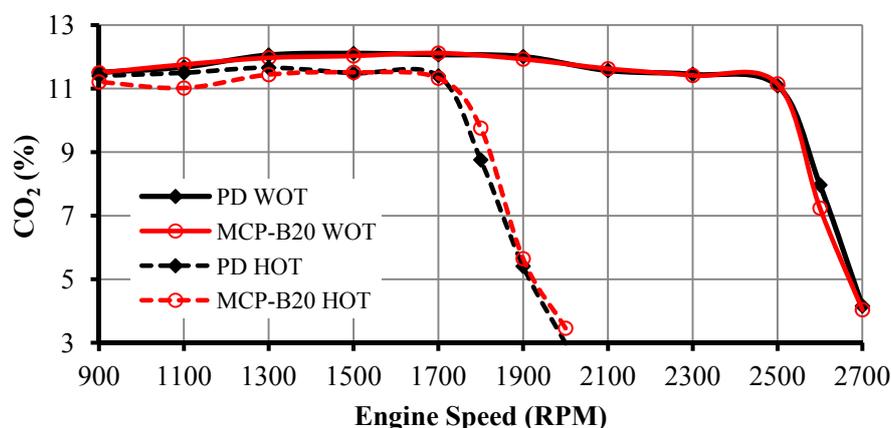


Figure 11 depicts the effect of tractor engine speeds (RPM) on CO₂ (%) for PD and MCP-B20. It is seen that the CO₂ (%) is relatively steady for the engine speeds below 2500 RPM for the WOT test and below 1700 RPM for the HOT test. The percentages of CO₂ then declined dramatically during both throttle tests for both fuels. The reason for this declination can be due to the lower load applied on the engine at the high speeds and the considerably lower fuel consumption rate makes the engine produce lower CO₂ (%). Figure 10 and Table 4 show that both fuels present very comparable percentages of CO₂ at most engine speeds. On the other hand, Table 3 illustrates that MCP-B20 significantly emits lower CO₂% than PD at rated PTO speed. This may be due to the reason that, in a complete combustion, the lower carbon to hydrogen ratio in biodiesel results in producing less CO₂ emissions from biodiesel than diesel [24]. The advanced air-fuel ratio with the increasing engine speed has improved the air-fuel mixing process in the combustion chamber which resulted in higher burning gas

temperatures. This condition converts more CO emissions to CO₂ emissions with much more CO₂ production.

It is important to mention here that PM, UTHC and CO are known products of incomplete combustion. One of the advantages of using microalgae fuel in diesel engine is to reduce black smoke in the exhaust gas. The formation of soot from exhaust emission is proportional with the change of combustion temperature. However due to unavailability of UTHC and soot measurement, the UTHC and PM were not reported.

Figure 11. The relationship between tractor engine speeds (RPM) and CO₂ (%) for PD and MCP-B20.



3.3.2. Oxygen (O₂) and Lambda (λ)

The results of the WOT test and HOT test which display the O₂ percentage against the tractor engine speeds are given in Figure 11. In stoichiometric air–fuel ratio and complete air–fuel mixing, the presence of O₂ in the exhaust gases gives an indication of the quality of combustion. It can be seen from Figure 12 that, at high engine speeds, the existence of O₂ in the exhaust gases increase for both fuels and both the WOT and HOT tests. This increase can be due to the higher air–fuel ratio at high engine speeds that come from low loads applied on the engine at high speeds. This result is confirmed by lambda results in Figure 13 which present a comparable pattern between O₂ and lambda. Diesel engines normally run with maximum air flow, while the fuel can be controlled. This shows the difference between WOT and HOT in which the air is constant but the fuel flow is reduced for the HOT test which justifies the lower O₂ percentage for the HOT test compared to the WOT test at the same speeds. Comparable results of O₂% are found between MCP-B20 and PD as shown in Figure 11 and Table 4. However, Table 3 shows a very high increase in O₂% when the tractor is fueled by MCP-B20 compared to PD at the rated PTO speed. As the same speed there is no significant difference in the engine efficiency between the two fuels, the reason for the higher O₂% may be due to the extra Oxygen in the biodiesel structure.

Lambda is the actual air–fuel ratio divided by the stoichiometric air–fuel ratio. When Lambda is higher than one, the engine runs lean, which is normal in diesel engines [22,26]. Lambda's values for the tractor engine when running on MCP-B20 and PD at WOT and HOT tests are graphically presented in Figure 13.

Figure 12. The relationship between tractor engine speeds (RPM) and O₂ (%) for PD and MCP-B20.

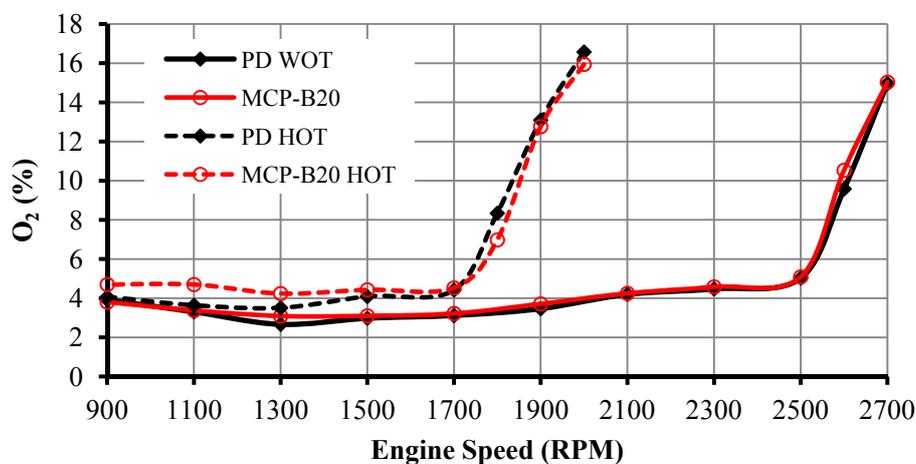
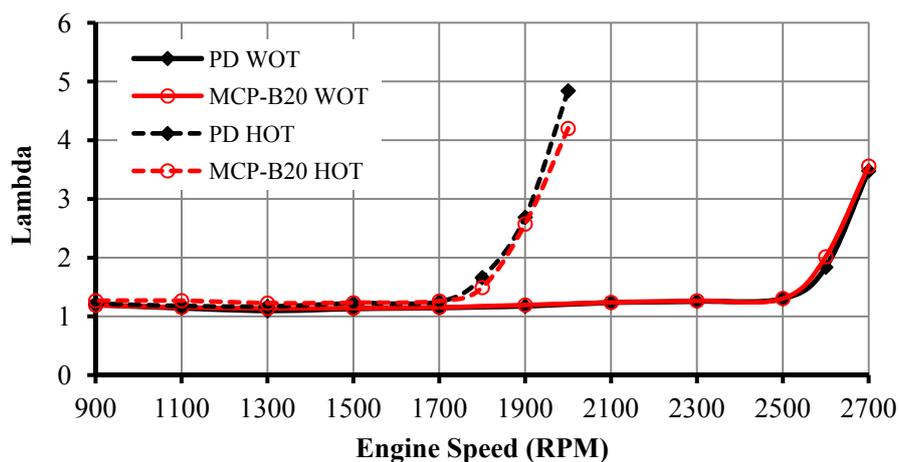


Figure 13. The relationship between tractor engine speeds (RPM) and lambda for PD and MCP-B20.

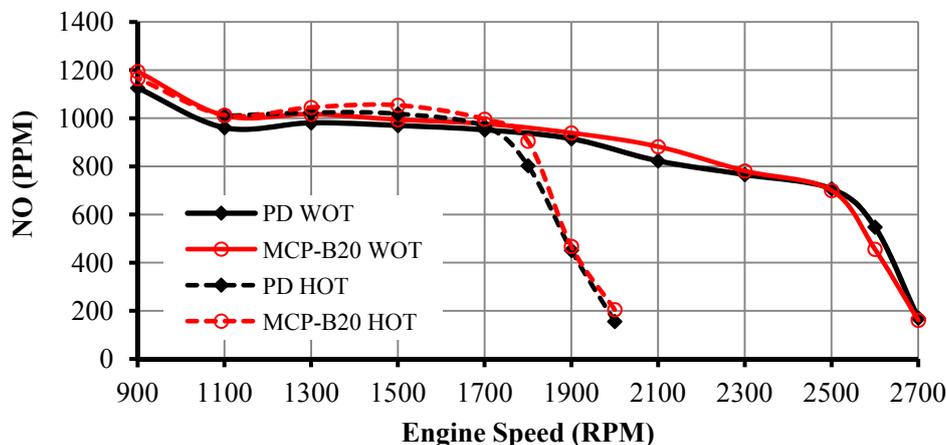


3.3.3. Nitrogen monoxide (NO)

Figure 14 shows the effect of the engine speeds on the NO emission measured by (PPM) for the tractor engine fuelled by PD and MCP-B20 for the WOT and HOT tests. A similar trend can be observed for both fuels for the WOT and HOT tests in the emission of NO. It can be seen from Figure 14 that NO emissions decrease when engine speeds increase by reducing the torque applied on the engine. Substantial differences are found between low and high engine speeds for both fuels. The maximum values of 1126 PPM and 1194 PPM at 900 RPM are found to decline to 170 PPM and 161 PPM for PD and MCP-B20 respectively. The increase of nitrogen oxides in diesel engines is due to the sufficient amount of oxygen, in-cylinder temperatures and the residence time of reaction at elevated temperatures. It can be seen from Figure 14 that MCP-B20 emitted slightly higher NO levels than PD at all the engine speeds for the HOT test and at most engine speeds at WOT. Table 3 and Figure 14 show that the increase in NO emission of MCP-B20 at WOT in comparison with PD is

statistically significant. This finding does not agree with the Kulkarni *et al.* [19] and Neel *et al.* [18] findings as they reported an insignificant difference between the NO_x from PD and biodiesel B20.

Figure 14. The relationship between tractor engine speeds (RPM) and NO (PPM) for PD and MCP-B20.



4. Conclusions

Microalgae is environmentally friendly, has high biomass and lipid productivity, and is a non-edible oil, thus it can be excellent alternative fuel for diesel engines in agricultural tractors. The results of this work demonstrated that MCP-B20 can be used commercially as fuel for tractors with no modification. The PTO tests for the tractor engine at WOT and HOT show that the tractor power, torque and BSFC at MCP-B20 and PD are close and acceptable. The emission results demonstrate great reduction in CO and CO₂ when MCP-B20 was used, which are very encouraging outcomes. The ANOVA analysis for two points at maximum PTO torque and power shows that there are significant reductions in the values of torque, power, CO and CO₂ emissions of MCP-B20. The next phase of this project will be focusing on using microalgae MCP-B100 in the same tractor. The results will be assessed and compared with PD.

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