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Performance, Emissions and Durability Studies on Diesel Engine Fuelled with a Preheated Raw Microalgal Oil †

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Abstract: Preheated Schizochytrium sp. raw microalgae oil (MAO) was evaluated as a fuel in a single-cylinder four-stroke diesel engine to produce a comparative study of MAO and diesel oil (DO) critical parameters. In particular, brake power, brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure (CP), exhaust gas temperature (EGT), both nitrogen oxides (NOx) and carbon monoxide (CO) emissions were investigated. Additionally, an engine durability test for longevity was undertaken over a 30-h period, using raw MAO as the fuel. The study demonstrated that the preheated MAO could be successfully used in a diesel engine smoothly. The use of MAO reduced the engine brake power by 26% and increased brake-specific fuel consumption by 20%. The most significant finding from this research study is that there was a significant reduction in NOx and CO emission by 42% and 60% when using raw MAO, respectively. Therefore, these findings demonstrate that algae oil is a highly credible fuel for use in diesel engines and offers a promising solution to diesel engine emissions.

Keywords: microalgae oil; raw microalgae oil; straight vegetable oil (SVO); biomass; bioenergy; durability; performance; emissions

1. Introduction

Energy consumption is a key driver of economic development and, consequently, is a pivotal societal global issue. The combination of economic activity with an increase in world population has resulted in an increasing demand for energy [1]. Currently, renewable energy contributes approximately 11% to the global primary energy demands. However, it is anticipated that by the year 2070, approximately 60% of all energy needs will be met by renewable energy sources [2]. Bioenergy has the potential to be a crucial aspect in the replacement of fossil fuels, and biofuels are a vital source of bioenergy. In particular, bioenergy can support the global demand for energy whilst also reducing the production of both air pollution (e.g., from particulates) and greenhouse gases associated with fossil fuel usage [3]. Converting raw biomass into a final energy product is possible using a number of different bioenergy technology options. Several conversion technologies have been designed which are adapted to suit the feedstock's specific physical attributes and chemical composition as well as the energy output required (e.g., heat, power, transport fuel) [4]. An important aspect of biofuel usage is the impact of kinematic viscosity on fuel spray. Consequently, several experiments have been conducted on this important topic [5]. Fuel properties can be altered prior to combustion by preheating the fuel, and this process is most commonly used in vessels which utilise heavy fuels.

A highly promising straight vegetable oil (SVO)-based third-generation biofuel is MAO. Microalgae offer a range of benefits over other biomass products. Microalgae are unicellular photosynthetic organisms which utilise light energy and carbon dioxide at a higher photosynthetic efficiency than plants grown for biomass [6]. It can be used as a biological photocatalyst with the capacity to reduce atmospheric CO_2 levels. Cultivation of microalgae can take place on land which is not suitable for the farming of food crops, such as ex-industrial zones or municipal wastewaters, and therefore microalgae does not attempt to compete with or displace arable land usage. Microalgae are found to be rich in oils and so can be used as biofuels using existing technology. Therefore, exploitation of microalgae does not require the development of new, innovative technology. Another advantage of microalgae is that it grows rapidly and can double its biomass in a 24-h period. Consequently, there is an increasing focus on the use of microalgae as a biofuel source which could help to replace the use of DO.

Different species of microalgae are available, and each has specific characteristics associated with biomass productivity, oil yield and biodiesel productivity [7,8]. Another important feature of MAO is that it offers additional economic value through co-products such as proteins or residual biomass after extraction of the oil. These co-products can be utilised as feed or fertilisers. Alternatively, they can be fermented to produce ethanol or methane [9].

Despite research interest, the volume of published material on topics such as the performance and emissions of diesel engines using raw MAO is extremely limited compared to literature associated with microalgae culture, oil extraction and biodiesel production. As a general rule, microalgae can be utilised in diesel engines in different forms such as direct injection (SVO) and biodiesel (transesterification). Microalgae biodiesel is one of the commonest alternative fuels sourced from microalgae. The utilisation of microalgae biodiesel in compression-ignition (CI) engines has been undertaken for a wide range of blends, up to B50. Pure biodiesel has also been tested, particularly from the Chlorella species, which offers worldwide availability. The results demonstrate that the blend closest to DO is B20 [10].

Whilst biodiesel offers both improved performance and lower emissions, the potential to use MAO as an SVO must be considered due to the simplicity of MAO production. The biodiesel production process involves expertise, highly specialised knowledge and dedicated equipment. To date, only a small amount of research has been undertaken on the use of MAO as an SVO in a CI engine. This research did not yield consistent results or was limited in size/scale. Several studies indicated that using SVOs in diesel engines results in poor performance and less emissions compared to DO. This is mostly a result of poor fuel atomisation caused by the SVO's physiochemical proprieties such as higher viscosity, higher density, lower heating value (LHV), etc.

However, the potential to optimise the injection system exists and can be achieved through a combination of preheating the MAO, which changes its properties and adjusting the injection system characteristics. Additionally, using MAO as an SVO in slow-speed diesel engines also has potential which could be effective. Slow-speed diesel engines are intended to be used with heavy oil, which has a higher viscosity than SVO and so the engine is designed accordingly and, consequently, failure of the injector system is far more unlikely. Preheating heavy fuels results in a reduction in the fuel viscosity, which improves spray quality, which, in turn, improves combustion efficiency. Some early assessments have been undertaken by the research community, and these indicate that there is genuine potential for microalgae to be an integral aspect of future green transport fuels as well as being used in the carbon sequestration process. This research paper intends to investigate the performance, emissions and durability of a diesel engine fuelled with raw MAO, without the chemical additives.

2. Materials and Methods

2.1. Microalgae Oil

A raw MAO, extracted from Schizochytrium sp. biomass and without chemical additive, was used in the diesel engine. The properties of the MAO and diesel oil (DO) are illustrated below in Table 1. A preheating process was applied to reduce the viscosity of the microalgae oil in order to alleviate any injection and combustion difficulties. This preheating of MAO was the only sample preparation process used before fuelling the engine. In the engine fuel system, the fuel passes through two other heating processes to maintain its temperature between 55 and 65 °C.

Table 1. Properties of the Schizochytrium sp. raw MAO and diesel oil.

Properties	Units	DO	MAO
Kinematic viscosity at 50 °C	cSt	1.811	19.67
Density	kg/m3	762.5	930
Calorific value	MJ/kg	42.8	36.84
Carbon	%	86	75.9
Hydrogen	%	14	10
Oxygen	%	0	14
Flashpoint	°C	52	180

2.2. Engine Setup and Test Procedure

The experimental test rig consisted of a naturally aspirated diesel engine connected to a 3-phase alternator and electrical heater as a load bank. The engine specification is shown in Table 2. A fuel flow measuring burette was connected to the fuel line via a two-way valve to allow fuels to be drawn from the burette when it switched to the measurement position. The MAO tank was partially covered by a 180 W, 120 V flexible heating blanket and a 125 W, 240 V rope heater was employed on the fuel system prior to the fuel pump. This arrangement was utilised in order to maintain the fuel temperature during the experiments as it could be affected by the viscous nature of the MAO. Both blanket and rope heaters were connected to a proportional integral derivative (PID) temperature controller so the fuel temperature could be monitored. A TESTO 350 XL exhaust gas analyser was mounted on the exhaust manifold to measure both NOx and CO emissions. A schematic diagram of the engine test rig is shown in Figure 1. This study was carried out at full engine load and 2000, 2400, 2800 and 3200 rpm engine speed. The baseline results were initially generated by running the engine with DO. The engine was warmed up by DO to intensify the average temperature within the combustion chamber (>500 °C) before utilising the MAO.

Table 2. Engine specification.

Lombardini 15 LD 225 Marine Diesel Engine	
Number of cylinders	1
Cycle	4-stroke
Power (kW)	3.5
Bore (mm)	69
Stroke (mm)	60
Fuel consumption (gr/kWh)	267
Compression ratio	21:1
Injection system	Direct

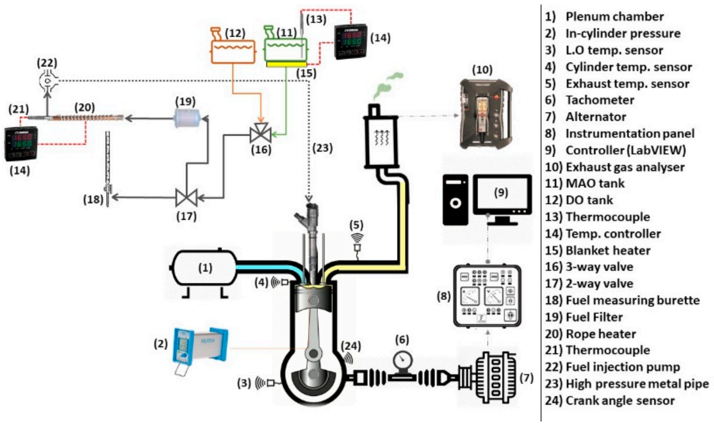

Figure 1. Schematic diagram of the engine test rig.

2.3. Error Analysis

Uncertainties or errors in these experimental measurements exist and consist of both random and systematic errors. The random error refers to an accidental and unanticipated change in the experimental conditions—for example, mechanical variation, electrical interference, sensor and temperature variation. The systematic error is non-random and is determined as the difference between the actual value and the mean value. In this project, the experimental error and uncertainty were calculated by using the statistical tolerance analysis method Root Sum Square (RSS), using the following equation:

$$\boldsymbol{RSS} = \sqrt{(\boldsymbol{\varepsilon s})^2 + (\boldsymbol{2\varepsilon r})^2} \quad (1)$$

where $\boldsymbol{\varepsilon s}$ is a system error, and $\boldsymbol{\varepsilon r}$ is random error. The relative errors of the measured data are illustrated in Table 3.

Table 3. Data accuracy and error analysis.

Parameter	Accuracy
Engine speed	10 ± rpm
Brake power	±2.5%
BSFC	±3%
BTE	±3%
EGT	±1%
ICP	±2%
CO	±5%
NO_x	±5%

3. Results and Discussion

The engine will behave differently when using MAO because of the property differences between DO and MAO. Crucial parameters including brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure (ICP), exhaust gas temperature (EGT), NOx and CO were investigated and analysed so that an assessment of performance and emissions characteristics could be made when MAO was utilised in a diesel engine.

3.1. Brake Power (BP)

Under normal conditions, BP increases as the engine speed increases. A graph of BP and engine speed for DO and B100 is shown in Figure 2. The maximum BP (2.24 kW) was achieved using DO. In comparison, at all speeds, the MAO was able to achieve approximately 75–81% of the DO generated BP. The difference in BP is a result of the property differences between MAO and DO, particularly in parameters such as lower heating value viscosity and oxygen content. Additionally, brake power is also affected by fuel density. This is because the density has an impact on the fuel injection as the injection system uses specific volume rather than a fixed mass quantity.

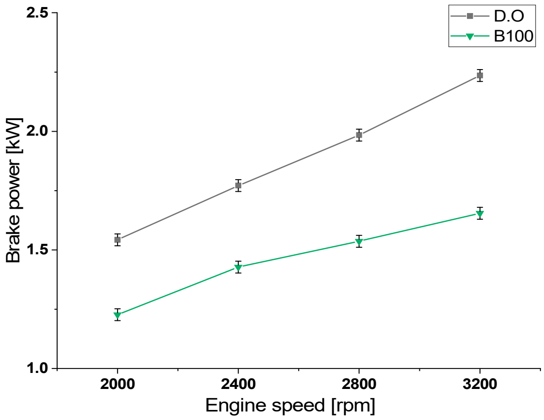

Figure 2. Brake power vs engine speed.

3.2. Brake-Specific Fuel Consumption (BSFC)

Figure 3 demonstrates the variation in BSFC for a range of engine speeds. It can be seen that the engine consumed nearly 20% more fuel when powered by MAO, and the trend increased as engine speed increased. This trend is probably predominately caused by the lower heating value of MAO, which causes the fuel system to inject more fuel to maintain speed. However, high kinematic viscosity and density of fuels can also contribute to an increased BSFC as both results in a decrease in the fuel satomisation and svaporisation [11]. Finally, the low-temperature rise could also be a contributing factor as it causes a lean combustion mixture. This can result in higher fuel consumption in low energy containing fuels, compared to fuels with higher heating values [12].

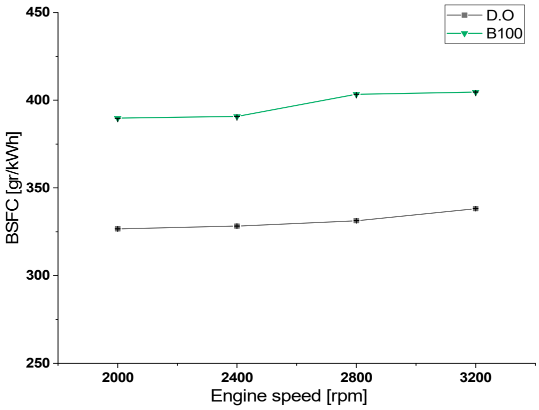

Figure 3. BSFC vs engine speed.

3.3. Brake Thermal Efficiency (BTE)

Figure 4 illustrates the variation in BTE for the test fuels. BTE is defined as the ratio of the BP developed by the engine to the thermal input from the supplied fuel. For MAO, the BTE results were marginally lower than the DO results and within measurement error limits. The minor reduction in BTE may be a result of the higher viscosity of the MAO, which results in poor fuel satomisation [13].

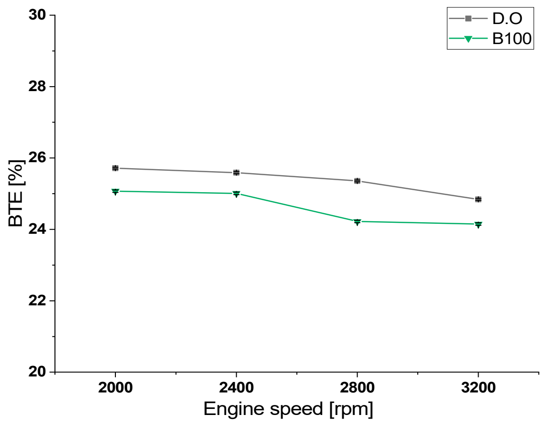

Figure 4. BTE vs engine speed.

3.4. Exhaust Gas Temperature (EGT)

Figure 5 shows the variation in EGT with engine speed and demonstrates that EGT, for both fuels, increases as engine speed increases, and this is a result of the higher amounts of fuel consumed. For the MAO, the EGT was less than DO EGT at all speeds, and the maximum reduction in MAO EGT was 22% less than DO. This difference in the EGT for DO and MAO is likely to be related to the different combustion profiles and engine heat loss.

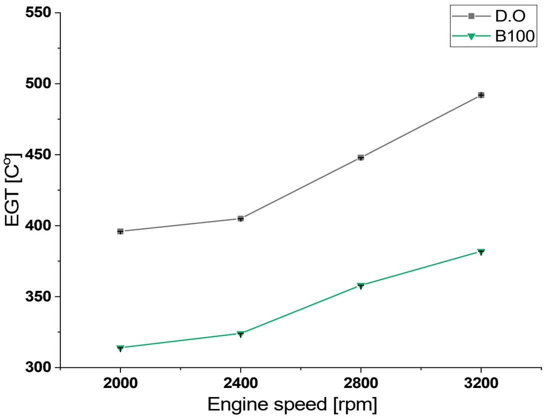

Figure 5. EGT vs engine speed.

3.5. Nitrogen Oxides (NOx)

Nitrogen oxides are one of the most critical emissions produced by diesel engines. NOx emission formation is highly dependent on fuel oxygen concentration and combustion temperature. Figure 6 demonstrates that the MAO has lower NOx emissions (16–42%) compared to DO. This is due to the higher cetane number of MAO as fuels with a higher cetane number have lower ignition delay, which results in a shorter duration of premixed combustion. It has been suggested that this shorter duration causes a slower rise in combustion pressure, leading to lower temperatures and a slower NOx formation rate [14].

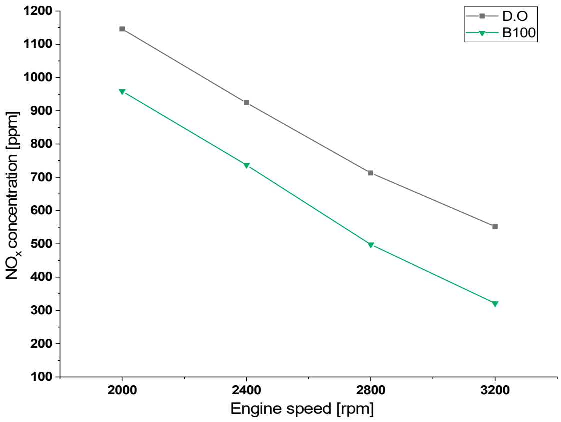

Figure 6. NOx vs engine speed.

3.6. Carbon Monoxide (CO)

Carbon monoxide is a toxic flammable gas formed due to a deficiency in oxygen during the combustion process. Figure 7 presents the CO emissions of MAO and DO. It can be observed that CO emissions are reduced for MAO at all speeds, with a maximum reduction of 60%, compared to DO. MAO has a longer ignition delay compared to DO, and this results in a greater proportion of the fuel being burned during the premixed combustion phase. Consequently, this results in improved fuel oxidation and less CO emissions for MAO and its blends. Work by Satputaley et al. and Işık et al. [13,15] indicated that higher oxygen content in the MAO results in complete combustion, resulting in a reduction in CO emissions. Moreover, in large diesel engines and especially in EU countries, CO emissions from biofuels can be considered as CO_2 neutral, which has an impact on costs and incentives if the CO is post-treated in an afterburner.

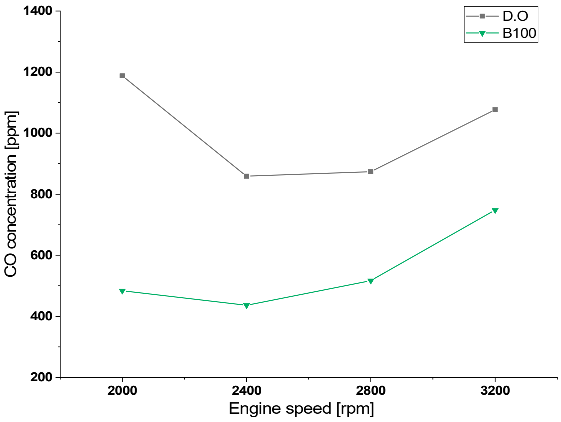

Figure 7. CO emissions vs engine speed.

3.7. In-Cylinder Pressure (ICP)

Figure 8a–d represent the variation in-cylinder pressure with respect to crank angle for the MAO and DO at different engine speeds. Both fuels experience a reduction in peak in-cylinder pressure with increasing engine speed, which can be attributed to the lower combustion duration at higher speeds. The figures show that no significant differences in in-cylinder peak pressure were observed between MAO and DO. As a result, the amount of heat released during combustion has no comparable difference.

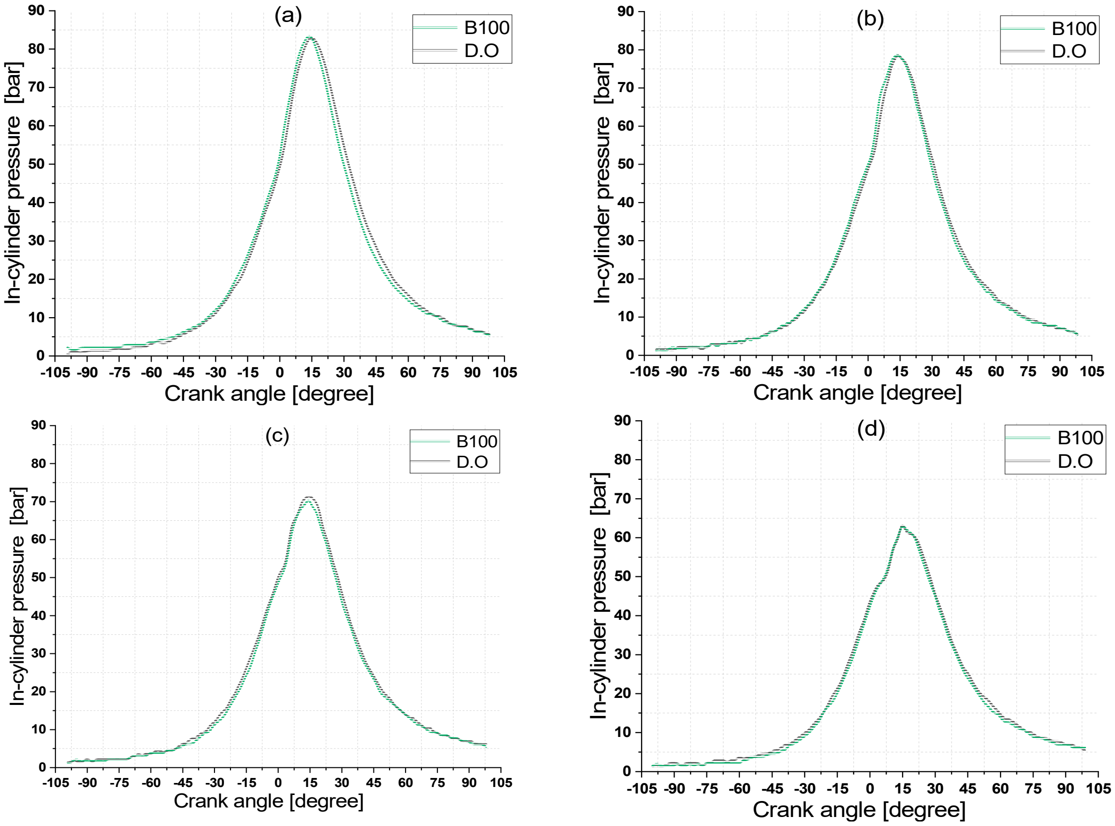

Figure 8. ICP vs. engine speed (**a**) 2000; (**b**) 2400; (**c**) 2800; (**d**) 3200.

3.8. Durability Test

In the long term, the use of raw vegetable oils in diesel engines may generate extremely concerning problems including an increase in toxic emissions and pollutants, reduction in engine power, degradation of lubricating oil (LO) due to deposit formation and wear and, fundamentally, irreparable damage to the engine. Due to limited supplies of MAO, the durability test was conducted for only 30 h using an ideal speed of 2400 rpm and a constant load (0.9 kW).

The engine was partially disassembled in order to observe the formation of deposits on the injector, piston top, valves and cylinder head. Photographs of formed carbon deposits on the engine parts are presented in Figure 9. At temperatures above 350 °C, carbon deposits are formed through two different processes: hydrocarbon decomposition, which forms carbon and other materials, and hydrocarbon condensation, which forms aromatic hydrocarbons with larger polynuclear components which aim to nucleate to form carbonaceous deposits [16].

Fuel properties also have a significant impact on deposit formation and production. Additionally, the lower heating value of MAO is lower than the value for DO. This results in an increased amount of injected fuel mass in the combustion chamber, as well as causing problems with evaporation. Finally, fuels with higher viscosities increase the delay ignition time and also the time to be vaporised. Consequently, this increases the tendency for deposits to form [17].

Figure 9. Deposit formation on engine parts.

4. Conclusions

From the experimental work conducted in this study, the following conclusions can be drawn:

- A reduction in brake power of up to 25% was observed, which is caused by the lower heating value, higher density and viscosity of the MAO.
- The lower heating value increased fuel consumption to produce constant output power, which led to an increase in the BSFC of 20%.
- No significant difference was found in BTE and in-cylinder pressure.
- The difference in combustion profile and heat loss from the engine when using MAO could account for the reduction in EGT.
- MAO NOx emissions were 42% lower than DO, primarily due to the shorter duration of premixed combustion.
- The MAO's longer ignition delay at full load results in improved fuel oxidation and therefore reduced CO emission.

This study demonstrates that MAO is feasible as a fuel in a diesel engine. It is probable that both performance and emissions can be improved via modifications to the engine design parameters, such as injection timing, injection pressure, nozzle diameter and compression ratio.

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References

1. Bahadar, A.; Khan, M.B. Progress in energy from microalgae: A review. *Renew. Sustain. Energy Rev.* **2013**, *27*, 128–148.
2. Ullah, K.; Ahmad, M.; Sofia Sharma, V.K.; Lu, P.; Harvey, A.; Zafar, M.; Sultana, S.; Anyanwu, C.N. Algal biomass as a global source of transport fuels: Overview and development perspectives. *Prog. Natl. Sci. Mater. Int.* **2014**, *24*, 329–339.

3. Metzger, J.O.; Hüttermann, A. Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas. *Naturwissenschaften* **2009**, *96*, 279–288.
4. Bioenergy, I. *Bioenergy—A Sustainable and Reliable Energy Source*; International Energy Agency Bioenergy: Paris, France, 2009.
5. Hossainpour, S.; Binesh, A.R. Investigation of fuel spray atomization in a DI heavy-duty diesel engine and comparison of various spray breakup models. *Fuel* **2009**, *88*, 799–805.
6. Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25*, 294–306.
7. Li, Y.; Horsman, M.; Wu, N.; Lan, C.Q.; Dubois-Calero, N. Biofuels from microalgae. *Biotechnol. Prog.* **2008**, *24*, 815–820.
8. Li, Y.; Horsman, M.; Wang, B.; Wu, N.; Lan, C.Q. Effects of nitrogen sources on cell growth and lipid accumulation of green alga Neochloris oleoabundans. *Appl. Microbiol. Biotechnol.* **2008**, *81*, 629–636.
9. Cantrell, K.B.; Ducey, T.; Ro, K.S.; Hunt, P.G. Livestock waste-to-bioenergy generation opportunities. *Bioresour. Technol.* **2008**, *99*, 7941–7953.
10. Piloto-Rodríguez, R.; Sánchez-Borroto, Y.; Melo-Espinosa, E.A.; Verhelst, S. Assessment of diesel engine performance when fueled with biodiesel from algae and microalgae: An overview. *Renew. Sustain. Energy Rev.* **2017**, *69*, 833–842.
11. Yahya, W.; Norhisyam, M. Utilization of waste cooking oil as diesel fuel and improvement in combustion and emission. *J. Mech. Eng. Auto.* **2012**, *2*, 267–270.
12. Yu, H. *The Design, Testing and Analysis of A Biofuel Micro-Trigeneration System*; Newcastle University: Newcastle, UK, 2013.
13. Satputaley, S.S.; Zodpe, D.B.; Deshpande, N.V. Performance, combustion and emission study on CI engine using microalgae oil and microalgae oil methyl esters. *J. Energy Inst.* **2017**, *90*, 513–521.
14. Kalligeros, S.; Zannikos, F.; Stournas, S.; Lois, E.; Anastopoulos, G.; Teas, C.; Sakellaropoulos, F. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. *Biomass Bioenergy* **2003**, *24*, 141–149.
15. Işık, M.Z.; Bayındır, H.; Iscan, B.; Aydın, H. The effect of n-butanol additive on low load combustion, performance and emissions of biodiesel-diesel blend in a heavy duty diesel power generator. *J. Energy Inst.* **2017**, *90*, 174–184.
16. Arifin, Y.M.; Furuhata, T.; Saito, M.; Arai, M. Diesel and bio-diesel fuel deposits on a hot surface. *Fuel* **2008**, *87*, 1601–1609.
17. Liaquat, A.; Masjuki, H.; Kalam, M.; Fazal, M.; Khan, A.F.; Fayaz, H.; Varman, M. Impact of palm biodiesel blend on injector deposit formation. *Appl. Energy* **2013**, *111*, 882–893.