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Algae to energy: Engine performance using raw algal oil

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Abstract

Modelling and simulation have vital roles in accelerating research, providing a more effective way to predict processes without the need to perform specific experimental tests. This study investigated the potential of using raw oil from microalgal biomass as a direct substitute fuel in an internal combustion engine. Based on the fuel properties of the algal oil, the performance and emission characteristics of a diesel engine running with this fuel were investigated using the software «Diesel-RK». The results were compared with croton oil as this provides a useful foundation for comparing this new fuel with other bio-oils and diesel fuels. Algal oil demonstrated lower engine power output and NO_x emissions compared to croton oil, whereas at the same time it showed higher break specific fuel consumption, particulate matter and CO_2 emissions.

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Keywords: Algae growth;oil extraction; engine performance;emission characteristics

1. Introduction

Microalgae are currently the most promising source of biofuels for total substitution of fossil fuels. Distinct benefits of microalgae compared to terrestrial feedstock include, but are not limited to, their higher photosynthetic efficiencies [1], and higher productivity which can potentially produce substantially greater biomass yields per day and per unit cropping area [2, 3]. The number of studies that have evaluated the potential of using raw algal oil in an engine are insufficient [4] to gain a full understanding of the likely performance of this fuel. The use of raw algal oil can overcome problems related with the use of expensive chemicals and procedures during the transesterification reaction necessary to produce biodiesel. The aim of this study was to evaluate the potential of using algae oil as the alternative fuel for diesel engines following controlled cultivation, harvest and oil extraction. The physicochemical properties of the oil were used to parameterise simulated runs of a diesel engine and the performance and emission characteristics were compared with an engine running with croton oil.

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2. Materials and methods

2.1 ALGAL CULTURE AND LIPID EXTRACTION

The marine chlorophyte *Tetraselmis suecica* was batch cultured in both natural and artificial seawater in five 10L polycarbonate flasks (carboys) with a constant 16 hours light/8 hours night photoperiod at 19±2°C temperature and 3000 lux light intensity. The medium had the following composition (per litre): 0.1 g $NaNO_3$, 0.056 g NaH_2PO_4, 4.16 mg Na_2EDTA, 3.15 mg $FeCl_3.6H_2O$, 0.01 mg $CuSO_4.5H_2O$, 0.022 mg $ZnSO_4.7H_2O$, 0.01 mg $CoCl_2.6H_2O$, 0.18 mg $MnCl_2.4H_2O$, 0.006 mg $Na_2MoO_4.2H_2O$, 0.0005 mg Cyanocobalamin (Vitamin B_{12}), 0.1 mg thiamine HCl (Vitamin B_1) and 0.0005 mg Biotin. Gas transfer and mixing was facilitated by use of an aquarium pump. Algal cells were harvested by centrifugation between 730 and 3520 g and washed twice with distilled water to reduce salinity levels. Lipid from freeze dried algae were extracted using a modified Folch method [5], as described in Iverson [6].

2.2 ANALYTICAL PROCEDURES

Lipid composition was determined based on the elemental analysis (using a CARLO ERBA 1108 elemental analyser) and the FAME profile. The latter was performed using a Hewlett 5890 Packard series 2 Gas Chromatograph. The FAME mixture was prepared directly from the algal biomass using Garches and Mancha method [7]. Briefly, 3.3 ml methylating mixture, which contained methanol, toluene, 2,2 dimethoxypropane and sulphuric acid, in 39, 20, 5, 2 volume ratio respectively was mixed with 1.7 ml of heptane. The mixture was added to 0.2 g of dry algal biomass and incubated at 50°C and 30 rpm. The higher heating value (HHV) of the oil was determined using CAL 2K-ECO bomb calorimeter.

2.3 MODELLING AND SIMULATION OF ENGINE PERFORMANCE USING ALGAL OIL

Based on the algal oil fuel properties analysed in the laboratory, the performance and emission characteristics of a diesel engine run with this fuel was investigated using the licensed software «Diesel-RK». Yu (2012) tested the performance and emission characteristics of a purchased croton oil (*Crotonis oleum*), in a Yanmar diesel engine, preheating the oil at 90°C [8]. The model was developed based on this particular engine and validated by the experimental results tested by Yu (2012) using croton oil [8]. The engine is a four stroke diesel engine with one cylinder, 92 mm cylinder bore and 92 mm piston stroke. The preheated temperature of both oils was set to 90°C.

3. Results and discussions

3.1 PHYSICOCHEMICAL PROPERTIES OF ALGAL OIL

The results of the GC-analysis of the algal oil are listed in Table 1. The algal lipids consisted of fatty acids between 16 and 20 carbon chain length. The higher concentration fatty acids were palmitic, stearic, oleic and linolenic acid. Table 1 also shows some of the most important physicochemical properties of algal and croton oil which were used for simulating an engine test running with the two fuels. The physicochemical properties of croton oil were obtained from Yu (2012) [8]. Algal oil has a lower carbon content compared to vegetable oils while at the same time having a larger amount of oxygen, which both justify the lower heating value of algal oil compared to croton oil. The difference in the composition of the two oils is explained by the higher amount of phospholipids, pigments (like chlorophyll) and waxes in algal lipids compare to commercial vegetable oils which have higher purity in triglycerides. The cetane number was calculated based on the saponification number and iodine value of the oil [9, 10], while the density and viscosity were estimated using soybean and crambe oil as reference, respectively [11, 12], as they have similar corresponding properties [4, 13]. As 323 Kelvin is the temperature which the software uses for the input of viscosity and density, both properties are given at that temperature. The results suggest that algal oil demonstrates higher cetane number, density and viscosity (both dynamic and kinematic) than croton oil.

Table 1 Fatty acid composition and physicochemical properties of algal and croton oil.

Fatty Acids	Proportions (wt%)	Properties	Algal oil	Croton oil [8]
C16:0	20.80	C (wt %)	67.91	76.9
C16:1	9.72	H (wt %)	10.69	11.6
C18:0	19.56	O (wt %)	19.86	11.5
C18:1	16.39	N (wt %)	1.54	/
C18:2	3.56	S (wt %)	/	0.001
C18:3	20.86	HHV (MJ/Kg)	32.79	39.60
C20:0	9.12	Cetane number	55.6	40.7
		Density at 323 K (kg/m3)	902.3	890.6
		Dynamic Viscosity at 323 K (Pa.s)	0.0319	0.0186
		Kinematic Viscosity at 323 K(mm^2/s)	35.4	20.9

3.2 ENGINE PERFORMANCE AND EMISSION CHARACTERISTICS OF ALGAL OIL BY SIMULATION

The algal oil's engine performance and emission characteristics (run by simulation) were compared with the croton's (figure 1). Algal oil produced lower engine power than croton, which is explained by the lower heating value of the former (figure 1a). On the other hand, algal oil demonstrated significantly higher brake specific fuel consumption (BSFC) at low loads (10%), while this difference is zeroing at higher loads (figure 1b). The lower energy density of algal oil compared to croton oil necessitated an increase in the volume of injected fuel to retain the same power output, increasing the BSFC in algal relative to croton oil. In addition, the high kinematic viscosity and density of fuels can cause decrease of the fuel atomization and vaporization, leading to high BSFC [14]. Moreover, at 10% engine load there is a low temperature rise, which causes a lean combustion mixture, thus it can trigger even higher fuel consumption in low energy containing fuels, compared to fuels with higher heating values [8]. In contrast, the higher oxygen content of algal oil compared to croton favours the complete combustion of the fuel leading to the reduction of the BSFC at higher loads, in which there is higher temperature rise compared to low loads [15]. In contrast, the CO_2 emissions of algal oil are higher at 25, 50 and 75% loads than croton oil, whereas at 10 and 100% loads CO_2 emissions are almost identical (figure 1c). This result is a combination of the higher carbon content of croton oil and, on the other hand, the higher viscosity and lower heating value of algal oil which causes the increase in BSFC, thereby increasing CO_2 emissions, as the CO_2 emissions are expressed on grams per output energy.

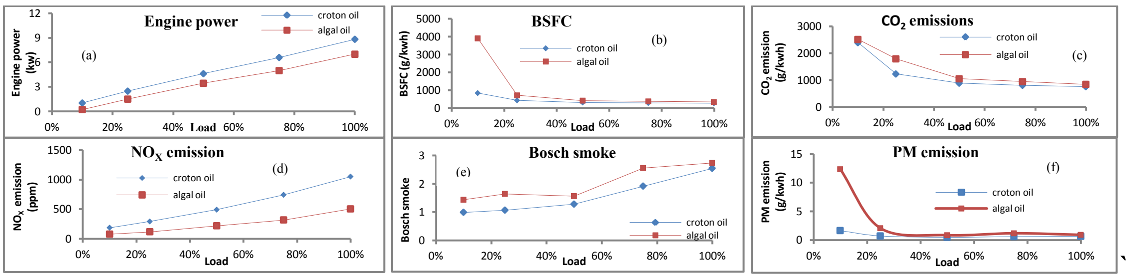

Fig. 1 Comparison of the (a) engine power, (b) BSFC, (c) CO_2 emissions, (d) NO_x emissions, (e) Bosch smoke number, and (f) PM emissions between croton and algal oil.

The higher cetane number of algal oil accounts for the lower NO_x emissions (figure 1d). Fuels with a higher cetane number have lower ignition delay, hence shorter duration of premixed combustion, which suggests a slower rise of combustion pressure, and as a result lower temperatures and slower NO_x formation rate [16]. On the other hand, the higher viscosity of algal oil compare to croton oil, alters the fuel atomization and increases the smoke emissions (Figure 1e) [17]. Finally, figure 3f suggests that the PM emissions of algae oil are significantly higher at 10% load, compare to croton oil, whereas at higher loads the emissions are almost equal. The significant increase of PM emission at low loads (10%) is a result of the high BSFC (figure 1b) which favours the accumulation of un-burnt emissions [8]. The lower sulphur content and of algal oil compared to croton oil, with at the same time a higher oxygen content, explains the significant reduction of PM emissions of algal oil at higher and full loads [16, 18]. Problems caused by the high viscosity (such as poor fuel atomization and obstruction of fuel lines and filters) of algal and croton oil could be resolved by increasing fuel injection temperature at 90°C for both oils [19].

Conclusions

The algal oil exhibited a negative influence on engine power, BSFC, CO_2 and PM emissions, while the NO_x emissions were lower with algal oil than croton oil. Nevertheless, algal oil is feasible as a fuel in a diesel engine as the performance and emissions are acceptable, especially at higher loads.

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