Biodiesel Production from Microalgae- A Sustainable Fuel

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ABSTRACT

With the ever increasing demand for diesel and environmental squalor caused by burning of diesel fuel, research for the development of a sustainable alternative fuel is being carried around all over the world. Biodiesel has become an attractive alternative to diesel fuel in last many years. However, availability of feedstock for biodiesel production has always been a matter of concern. Micro-Algae are considered a very good feedstock for biodiesel production due to their very high yield and their no competition with food crops. Oil productivity of many micro-algae greatly exceeds the oil productivity of the best oil producing crops. This research paper examines the potential suitability of biodiesel made from micro-algae of Indian origin. The trial conducted on diesel engine with algae biodiesel shows that the results are comparable to diesel fuel.

Keywords: Algae, Biodiesel, Transesterification

1. INTRODUCTION

The world is entering a period of declining non-renewable energy resources; popularly know as “Peak Oil”, while energy demand is increasing [1]. India, like any other developing country, relies on energy for sustained growth & development and consequently depends on crude petroleum imported from other countries to cater to the large demands of fuel in the automobile, industrial and agricultural sectors. India produced 34.11 million tones of crude oil in 2007-08, and imported 121.67 million tones of crude oil worth Rs.2726.99 billion. Over reliance on petroleum derived fuels has caused carbon dioxide (CO_2) enrichment of the atmosphere which has already reached the “dangerously high” threshold of 450 ppm. The annual mean growth rate for 2007 was 2.14ppm – the fourth year in the past six to see an annual rise greater than 2ppm [2]. In India, emissions from energy use in transport and industrial sectors are higher than in agriculture sector (3). The researchers have the daunting challenge to find out sufficient supplies of clean energy for the future, which is intimately linked to global sustainability, economic prosperity, and quality of life [1]. Diesel Engine plays a very important role in Indian economy but contributes to pollution significantly. These engines are used in heavy trucks, city transport buses, locomotives, electric generators, farm equipment, underground mine equipment etc [4, 5]. Indian economy is essentially diesel driven and the consumption of diesel fuel is four to five times more than motor-gasoline which is characteristically different from several developed economies. Therefore in Indian context, there is an urgent need to identify and commercialize renewable alternative fuels for diesel substitution.

Biodiesel has become a sustainable substitute to diesel fuel as biodiesel is produced from vegetable oil or animal fat through a chemical process known as transesterification. Research on different aspects of biodiesel production and utilization in diesel engine has been reported by a number of researchers [6-14]. Biodiesel can be used as either direct substitute or as an extender to fossil diesel fuel in compression ignition engines and has the potential to reduce carbon dioxide, hydrocarbon and carbon monoxide emissions. Biodiesel is currently produced from the oil synthesized by conventional fuel crops like Jatropha and Karanja that harvest sun’s energy and store it as a chemical energy. In Indian context, Jatropha is the most potential crop for biodiesel production. Jatropha Curcus is a hardy plant and can even thrive on waste and degraded land [15].

Table 1: Yield per acre of various feedstocks (17)

Source	Oil Yield (l/ha)	Area to produce global oil demand (ha × 10^6)
Cotton	325	15,002
Soyabean	446	10,932
Mustard Seed	572	8,524
Sunflower	952	5,121
Rapeseed/Canola	1,190	4,097
Oil Palm	1,892	2,577
Jatropha	5,950	819
Corn	172	1,540
Canola	1,190	223
Algae[a] (10g/m^2/day at 30% TAG)	12,000	406
Algae[a] (50g/m^2/day at 50% TAG)	98,500	49

Biodiesel from microalgae seems to be the only renewable biofuel that has the potential to completely displace petroleum-derived transport fuels without adversely affecting supply of food and other crop products [16]. Algal ponds and bioreactors for algae production are situated on non-arable land; however, Jatropha is mainly grown on marginal land [17]. Availability of feedstock for biodiesel production has always been a matter of concern and challenge for biodiesel industry and in this context, yield of biodiesel crop should be as high possible for biodiesel industry to survive. Table 1 summarizes the yield per acre of various feedstocks.

2. MICROALGAE, AN ALTERNATIVE BIODIESEL FEEDSTOCK

Microalgae are sunlight- driven cell factories that convert carbon dioxide to potential biofuels, foods, feeds and high value bioactives [18]. It contains lipids and fatty acids as membrane components, storage products, metabolites and sources of energy. Algal strains, diatoms, and Cyanobacteria (categorized collectively as "Micro-algae") have been found to contain proportionally high levels of lipids (over 30%) [19]. Microalgal biomass, like other plant biomass, is potentially suitable for conversion to liquid (gasoline, biodiesel, ethanol) and gaseous (methane, and hydrogen) fuels [20]. Most of the oleaginous microorganisms like microalgae, bacillus, fungi and yeast are all available for biodiesel production [21].

Microalgae have a number of unique benefits. As aquatic species, they do not require arable land for cultivation. This means that algae cultivation does not need to compete with agricultural commodities for growing space. In fact, algae cultivation facilities can be built on marginal land that has few other uses. Algae also have a greater capacity to absorb CO_2 than land plants, and are not prone to photosynthetic inhibition under conditions of intense sunlight. After oil extraction from algae, the remaining biomass fraction can be used as a high protein feed for livestock which gives further value to the process and reduces waste [1]. Microalgae appear to be the advantage of costs depending on its capability of higher photosynthetic efficiency, larger biomass and faster growth rate compared to that of oil crops. Oil content of many microalgae is usually 80% of its dry weight [22]. Depending on species, microalgae produce different kinds of lipids, hydrocarbons and other complex oils. Not all algal oils are suitable for making biodiesel; however,

Table 2: Oil Content of some microalgae (18)

Microalgae	Oil Content (% dry weight)
Botryococcus braunii	25-75
Chlorella sp.	28-32
Crypthecodinium cohnii	20
Cylindrotheca sp.	16–37
Dunaliella primolecta	23
Isochrysis sp.	25–33
Monallanthus salina	›20
Nannochloris sp.	20–35
Nannochloropsis sp.	31–68
Neochloris oleoabundans	35–54
Nitzschia sp.	45–47
Phaeodactylum tricornutum	20–30
Schizochytrium sp.	50–77
Tetraselmis sueica	15–23

suitable oils occur commonly. Using microalgae to produce biodiesel will not interfere with the production of food, fodder and other products derived from crops. The micro-algal strains with high oil or lipid content are summarized in table 2 and are of great interest in the quest for a sustainable feedstock for the production of biodiesel [18]. Microalgae are currently cultivated commercially for human nutritional products around the world in several dozen small- to medium-scale production systems, producing a few tens to a several hundreds of tons of biomass annually. About half of this production takes place in mainland China, with the rest in Japan, Taiwan, U.S.A., Australia and India, and a few small producers in some other countries [23].

Microalgae cultivation using sunlight energy can be carried out in open or covered ponds or closed photobioreactors, based on tubular, flat plate or other designs. Closed systems are much more expensive than ponds, and present significant operating challenges (overheating, fouling), and due to gas exchange limitations, among others, cannot be scaled-up much beyond about a hundred square meters for an individual growth unit [23]. Unlike open ponds, photobioreactors essentially permit single-species culture of microalgae for prolonged durations. Photobioreactors have been successfully used for producing large quantities of microalgal biomass [18]. Xu et al. extracted microalgal oil from the heterotrophic cells using n-hexane, and then transmuted it into biodiesel by acidic transesterification. The heating value of biodiesel was found to be 41MJkg^{-1}, the density as 0.864kgL^{-1}, and the viscosity as 5.2×10^{-4} Pas (at 40°C) [24]. Xiaoling et al. compared biodiesel from heterotrophic microalgal oil by acidic transesterification with conventional diesel. The results suggested that the new process, which combined bioengineering and transesterification, was a feasible and effective method for the production of high quality biodiesel from microalgal oil [25]. Umdu et al. studied activities of Al_2O_3 supported CaO and MgO catalysts in the transesterification of lipid of yellow green microalgae, Nannochloropsis oculata, as a function of methanol amount and the CaO and MgO loadings at 50 °C. They found that pure CaO and MgO were not active and CaO/Al_2O_3 catalyst among all the mixed oxide catalysts showed the highest activity [26].

3. MATERIALS AND METHODS

3.1. SITE

The experiments were carried out at Biodiesel Production and Testing Center, Delhi College of Engineering, University of Delhi, India.

3.2. SAMPLE COLLECTION

Algae strain (Chlorella) was collected from Indian Agricultural Research Institute (IARI), New Delhi

3.3. ALGAE CULTURE MAINTENANCE

The collected Algae culture was maintained in a +N medium form. This algae culture was firstly developed to the required quantity in a culture room providing the proper medium and micro nutrients. The ingredients of the +N medium and micro-nutrient solution were experimentally derived after carrying out series of experiments for Chlorella and are given in the table 3. The algae mass production was carried in Algae Photo-Bioreactor developed by Delhi College of Engineering. The harvesting was carried out when algae was fully grown. After drying the algae, oil was extracted from the algae using solvent extraction method. The transesterification of the algal oil was carried out in a biodiesel reactor developed by the institute.

Table 3: Algae Medium and Nutrient Solution Constituents

Medium (BG-11) +N	**A-5 (Micro Nutrient Solution)**
Chemicals Stock Solution (per 200ml of distilled water)	Chemicals dissolved in 1 liter of distilled water
$NaNO_3$ (30g)	H_3BO_3 (2.86g)
K_2HPO_4 (8g)	$MnCl_2.4H_2O$ (1.81g)
$MgSO_4.7H_2O$ (15g)	$ZnSO_4.7H_2O$ (0.222g)
CaCl2.2H2O (7.25g)	$Na_2MoO_4.2H_2O$ (0.39g)
Citric Acid (1.2g)	$CuSO_4.5H_2O$ (0.079g)
Ferric Ammonium Citrate (1.2g)	
EDTA (Disodium Magnesium salt) (200mg)	
Na2CO3 (4g)	
1 ml of each stock solution was taken for 1 liter of algae growth medium	1ml of micronutrient solution was taken for 1 liter of algae growth medium

3.4. TEST ENGINE

Considering the wide application of a diesel engine in Indian agriculture sector, a medium capacity, direct injection agriculture diesel engine was selected for the present study. It is a single cylinder, four strokes, vertical, air-cooled diesel engine. The compression ratio is 17.5. It develops 7.4 kW brake power at rated speed of 1500 rpm with diesel as fuel. It has the provision of loading electrically since it is coupled with single phase alternator through flexible coupling.

3.4.1. ENGINE TESTING PROCEDURE

The tests were carried out at steady states with different loads of 0%, 20%, 40%, 60%, 80% and 100% at the engine maximum torque speed of 1500 rev/min. The engine was initially run on diesel fuel to generate base line data and after that it was run on algae biodiesel. Similar loading conditions were used for both the fuels. The smoke opacity was measured with an AVL 437 smoke meter and the exhaust emissions were measured by AVL 4000 Light 5 Gas analyzer. The original mechanical in-line fuel injection system was used for injecting diesel or biodiesel, and the fuel injection timing was not adjusted throughout the tests. At each engine mode, the engine was allowed to run for a few minutes until the exhaust gas temperature, the lubricating oil temperature and the gaseous emissions concentrations reached steady-state values and data was measured subsequently.

4. RESULTS AND DISCUSSION

4.1. PHYSICO-CHEMICAL PROPERTIES

The different physico-chemical properties of biodiesel were evaluated in accordance with ASTM D6751. The higher calorific value of algae biodiesel is 39.524 MJ/kg. The kinematic viscosity and specific gravity are 5.6 cSt and 0.869 gm/cc respectively which are slightly higher than diesel fuel. The flash point is considerably higher for algae biodiesel. The CHNSO analysis of algae biodiesel was carried and carbon was 77.32%, hydrogen as 12.74% and oxygen as 9.94%. Sulfur was found as 10 ppm and nitrogen as 7ppm. As the biodiesel is methyl ester of fatty acid, it does not have alkane or alkene. The algae biodiesel was stable and the shelf life was around 4 to 6 months without additive. The biodiesel was found to absorb very little amount of water when exposed to atmosphere. The value of Cetane index for algae biodiesel is above 47 suggesting better ignition quality. The values of carbon residue were higher in case of biodiesel than diesel. It was found that all the physico-chemical properties of biodiesel derived from algae were under prescribed limits of ASTM.

4.2. ENGINE RUN RESULTS AND DISCUSSION

4.2.1. BRAKE THERMAL EFFICIENCY

A graph of brake thermal efficiency (BTE) vs. brake mean effective pressure (BMEP) is shown in figure 1. From the test results of algae biodiesel, it was observed that brake thermal efficiency of mineral diesel is higher than algae biodiesel. It was also observed that the power produced by algae biodiesel is lower than that by mineral diesel. This may be due to the lower calorific value of algae biodiesel and its higher density and kinematic viscosity. The lower brake thermal efficiency obtained for AB100 fuel could be due to the reduction in calorific value and increase in fuel consumption as compared to diesel fuel. This indicates that the thermal efficiency is a better representative reflection of the fuel economy by using the diesel equivalent energy consumption rate when operated on oxygenated fuels like algae biodiesel. These results are similar to the results obtained by Raheman et al. in their studies [27].

4.2.2. CO EMISSIONS

Figure 2 depicts the CO emissions versus brake mean effective pressure for different biodiesel fuels. CO emissions were found to be lower for algae biodiesel. As the load is increased on the engine, there is an increase in CO emission for both fuels. The increase in CO emission levels at higher load is due to richer mixture at higher load condition than at lower load which results in incomplete combustion of fuel. Within the experimental range, the lower CO emissions have been observed with AB100 sample. This is possible since biodiesel contains more oxygen than diesel most of the carbon monoxide is converted into carbon dioxide and hence complete combustion takes place. The maximum value of carbon monoxide present in Algae Biodiesel (AB100) is 0.4% and the corresponding value of CO present in diesel is 0.61% which is significantly higher than that in algae biodiesel [28].

4.2.3. UBHC EMISSIONS

Figure 3 shows the variation in unburned Hydrocarbon Emissions vs brake mean effective pressure for algae biodiesel and diesel. The unburned hydrocarbon emissions are found lower at partial load conditions and increases at higher engine load. This is due to relatively less oxygen available for the reaction when more fuel is injected into the engine cylinder at higher engine load. The value of unburned hydrocarbon emission from no load to full load is higher in case of diesel as compared to algae biodiesel. Hydrocarbon emissions are mainly caused due to the incomplete combustion of hydrocarbon fuel. The maximum reduction in UBHC was achieved for algae biodiesel. The pattern of UBHC variation follows the same trend as reported by Canakci [29].

4.2.4. NO_X EMISSIONS

NO_x emissions from diesel engine fueled with algae biodiesel and diesel at different load conditions are shown in figure 4. Kinetics of NO_x formation is governed by Zeldovich mechanism. The principal source of NO_x formation is the oxidation of atmospheric nitrogen at sufficiently high temperatures. The NO_x emissions are determined by equivalence ratio, oxygen concentration, combustion temperature and time [30].

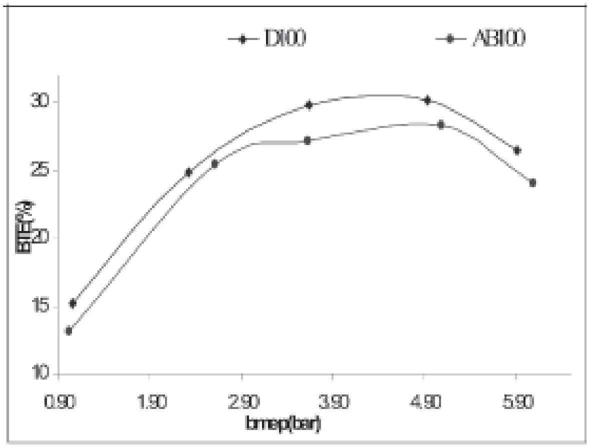

Figure 1. BTE vs BMEP

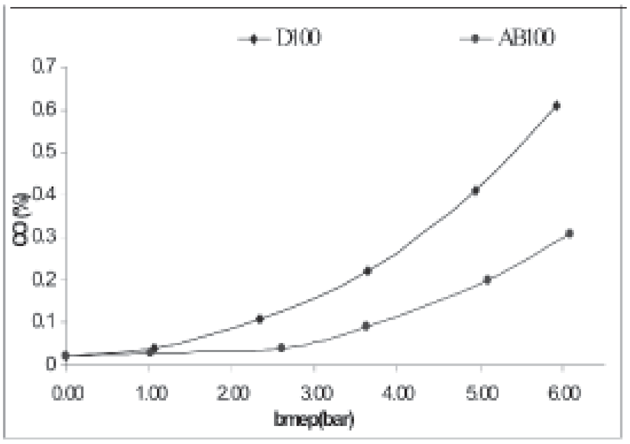

Figure 2. CO vs BMEP

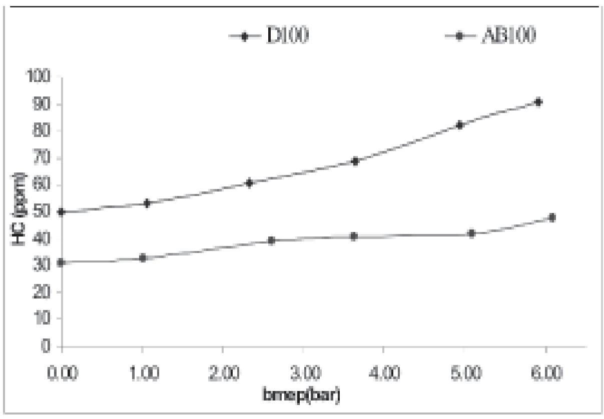

Figure 3. HC vs BMEP

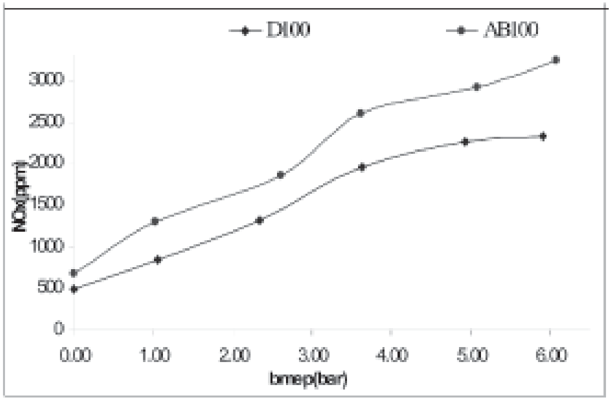

Figure 4. NO_x vs BMEP

NO_x are formed in cylinder areas where high temperature peaks appear mainly during the uncontrolled combustion. The NO_x emissions of algae biodiesel has been found higher than diesel at higher loads. The NO_x emission for algae biodiesel fuels is much higher than the diesel from no load to full load conditions. The maximum value of NO_x emissions for AB100 at full load is 3129ppm. This is the most important emission characteristic of biodiesel as the NO_x emission is the most harmful gaseous emissions from engines and this emission can be reduced by several methods. The results related to NO_x emissions are very much similar to earlier studies reported by Nabi et al. [31].

4.2.5. SMOKE OPACITY

Figure 5 indicates smoke opacity versus brake mean effective pressure for diesel and Algae biodiesel. It can be seen that smoke opacity is high mainly at high power outputs. High loads imply that more fuel is injected into the combustion chamber and hence incomplete combustion of fuel is prominent. Reduction of smoke emissions for algae biodiesel in comparison to diesel fuel has been achieved for all load conditions. The reduction in smoke can be explained by the presence of lesser amount of carbon in algae biodiesel as compared to diesel. In addition to that, algae biodiesel has more oxygen content contrary to diesel, which has no oxygen. The presence of oxygen in the biodiesel is in favour of carbon residual oxidation, which leads to reduction in smoke opacity. The smoke is produced mainly in the diffusive combustion phase, the addition of oxygenated fuel such as biodiesel leads to an improvement in diffusive combustion. Moreover, it was found that smoke opacity decreases more at higher loads than lower loads. This is quite practical as more fuels are supplied for larger load; short time is available for preparation of the air/fuel mixture as already mentioned. This factor leads to the improvement of combustion quality for algae biodiesel when compared with diesel fuels. These results are in agreement with the results reported by Puhan et al. [32].

4.2.6. COMBUSTION CHARACTERISTICS

The analysis of combustion characteristic of diesel, and algae biodiesel fuels were carried out. The graph showing in-cylinder pressures and rate of net heat release vs. crank angle of the diesel engine fueled with algae biodiesel fuel and diesel at full load conditions are shown in Figures 6 and 7 respectively. It is clear from figure 7 that ignition of fuel starts earlier for algae biodiesel in comparison to diesel fuel. Maximum cylinder gas pressure was found to be lower for algae biodiesel. In diesel engine, cylinder pressure depends on the burnt fuel fraction during the premixed burning phase, i.e., initial stage of combustion. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. High peak pressure and maximum

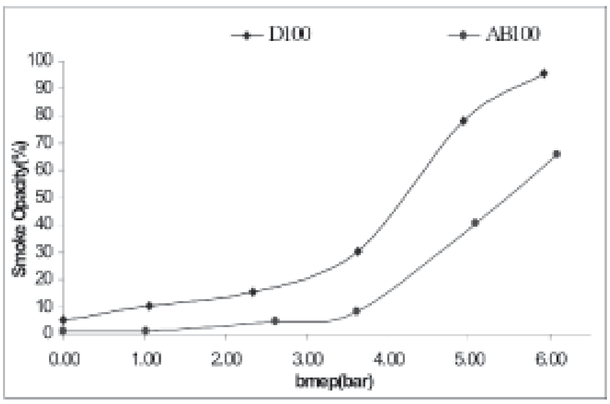

Figure 5. Smoke Opacity vs BMEP

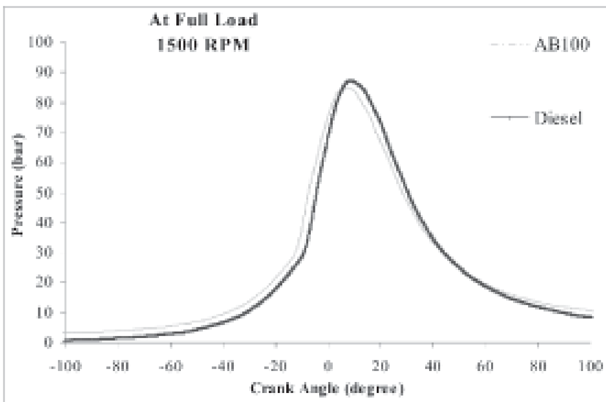

Figure 6: Pressure-Crank Angle Diagram for two fuels

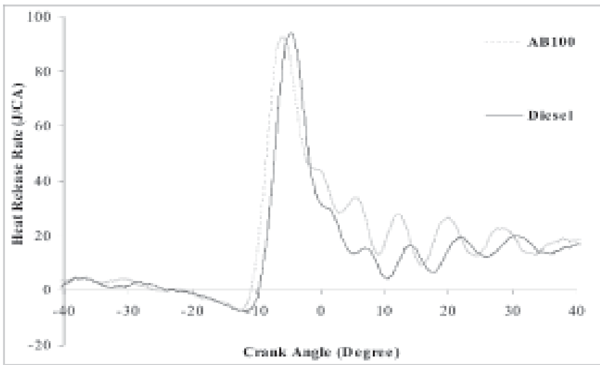

Figure 7: Net Heat Release Rate Diagram for two fuels

rate of pressure rise correspond to large amount of fuel burnt in premixed combustion stage. The value of peak cylinder pressure has been found lower for AB 100 fuel. It may be due to shorter ignition delay and more fuel burnt in diffusion stage.

Generally, it has been observed that biodiesel have higher cetane number than conventional diesel fuel. Shorter ignition delay causes lower peak heat release rate due to lower accumulation of the fuel. Therefore, premixed combustion heat release is higher for diesel, which is responsible for higher peak pressure and higher rates of pressure rise in comparison to different biodiesel-diesel blends. The ignition delay was calculated from the heat release rate which is the difference between the injection timing and the ignition timing results (taken as the time that the heat release is positive) and ignition delay was found to be higher for diesel fuel and lower for biodiesel fuel. The combustion characteristics follow the same trend as reported by Sahoo et al. [33].

5. CONCLUSIONS

This work investigated the production of biodiesel from microalgae of Indian origin and performance study of diesel engine with diesssel fuel and algae biodiesel. The results of this report are summarized as follows:

- Algae were produced by algae photobioreactor and the transesterification process was carried out to produce algae biodiesel
- The brake thermal efficiency of algae biodiesel was lower than diesel fuel due to lower calorific value, higher density and kinematic viscosity.
- Algae biodiesel showed the reduction in emissions of CO, HC and Smoke Opacity as compared to diesel whereas NO_x have been found to be higher for algae biodiesel.
- As the ignition delay is lower for algae biodiesel, the net heat release rate for algae biodiesel is found to be lower as compared to diesel.

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