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Research Article

An experimental evaluation of Chlorella emersonii biodiesel for compression ignition engines

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ABSTRACT

An increase in population count and a desire to reduce environmental hazards make researchers search for fuel that can be eco-friendly and combat the setbacks of conventional fossil fuel. Chlorella emersonii is a common freshwater green algae found in India. This oil is transesterified and converted to Chlorella emersonni methyl ester (CEME) biodiesel to mainly reduce viscosity and improve a few other properties. In the experiment, blending of CEME biodiesel with diesel was done on a volume basis, and B10 (100% CEME and 90% diesel), B20 (20% CEME and 80% diesel), B30 (30% CEME and 70% diesel), and B100 (100% CEME) were prepared for testing in a stationary single-cylinder diesel engine. Test results showed that B30 exhibited better results than others with high brake thermal efficiency, fewer emissions of HC by 24%, CO by 50%, smoke by 56%, and high cylinder pressure and heat release rate (HRR). Thus, the obtained results are close to diesel.

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INTRODUCTION

The scientific community has already conducted a great deal of work on biodiesel, such as increasing viscosity. The functioning of diesel engines running on biodiesel was thoroughly examined. A thorough survey was conducted, and more research on biodiesel made from algae was prioritised. These evaluations assisted in locating a unique biodiesel based on algae. In order to reduce emissions without affecting engine performance, greater attention was placed on emission management with the addition of fuel-borne additives to biodiesel. Optimisation of the strength of nanoparticles in biodiesel was studied. In an experiment with a stationary diesel engine, Haik et al. [1] used algal oil made from Nannochloropsis sp. and Ankistrodesmus. Methyl ester of algae oil used in diesel engines showed higher HRR and lower torque, and it also showed that retarding injection timing reduced emissions, improved torque, and reduced engine operating noise. Scragg et al. [2] used emulsified Chlorella vulgaris algae biodiesel and rapeseed biodiesel. Rapeseed oil (80% and algae oil (20%) are used for study in stationary diesel engines. This engine operated with emulsified fuel and exhibited reduced NOx emissions, exhaust gas temperature, and carbon dioxide. An increase in carbon monoxide and hydrocarbons was obtained. A slight improvement in BTE

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is observed compared to conventional diesel fuel. Tsousis et al. [3] tested marine chlorophyte algae (Tetraselmissucica) in diesel engines and compared them with croton oil (Crotonisoleum). Algae oil showed improved BSFC, high smoke particulates with reduced NOx emissions, and engine brake power compared to Croton oil. The surge in emissions was accounted for by the higher density, cetane number, viscosity, and oxygen content of algae oil compared to Croton oil. Jayaprakash et al. [4] experimented with a single-cylinder diesel engine using the algae methyl ester of Gracilaria verrucosa (AME) at various injection techniques. The obtained results were compared with the methyl ester of rice bran oil (RME). AME showed lower brake thermal efficiency, smoke, and HC, and higher NOx and BSFC. They compromised with a 20% AME blend and performed well with a slight alteration in advancing injection timing. Islam et al. [5] performed an experiment in a 5.2 kW stationary experimental diesel engine using microalgae oil from Chlorella protothecoides (MAO) and its methyl ester (MAME). Experimental outcomes showed lowered brake thermal efficiency and cylinder pressure by 5.6% and 3.09%, respectively, compared to diesel. Marginal reductions in HC, CO, smoke, and NOx emissions are observed. A higher peak pressure of 64.4 bar was noted for diesel, followed by 61.32 bar for MAME and 58.52 bar for MAO. Makareviciene et al. [6] have done an experiment using a stationary diesel engine fuelled with the methyl ester of a Jatropha-algae oil mixture. Different blends were prepared and evaluated in diesel engines. Test engines were made to operate with 0.5, 1, 1.5, and 2.2 kilowatt loading conditions. Results showed better BTE, BSFC, and lowered emissions of hydrocarbons, carbon monoxide, NOx, and smoke for the biodiesel mixture than usual diesel and their individual methyl ester fuels. Better results were obtained for the B20 blend (10% algae oil and 80% diesel) in all aspects. Kumar et al. [7] purposely experimented with diesel engines fueled with Chlorella vulgaris biodiesel. B20 blend (20% methyl ester of Chlorella vulgaris + 80% diesel) was prepared and tested in the engine. Fuel properties were found initially, and they were in range with diesel. A minor increase in thermal efficiency with high pressure and a high heat release rate was observed. Lowered emissions of HC, CO, NOx, and smoke were also achieved. Jayaraman et al. [8] experimented with biodiesel derived from freshwater algae in a single-cylinder, four-stroke, direct-injection diesel engine. One-step transesterification was done to convert raw oil to biodiesel. Three different alcohols are used for work, and their blends with proportion B20 (20% algae biodiesel + 80% diesel) were prepared. Fuel properties were found using ASTM standards. Final results showed that BTE was very close to base diesel fuel. BSFC were slightly higher. Reduced CO and HC emissions were noted. Oxides of nitrogen were slightly higher than diesel. Methyl ester (the methanol alcohol used) showed better performance and emission results. Lin et al. [9] experimented with methyl ester from Chlorella emersonii in a CI engine. Chlorella emersonii methyl ester (CEME) was blended on a volume basis of 10, 20, 30, 40, and 100% with diesel. Properties were found using ASTM standards. B20 (20% CEME+80% diesel) exhibited better thermal efficiency and reduced emissions such as hydrocarbon, carbon monoxide, and smoke. A slight increase in NOx and CO_2 is noted. Peak pressure and HRR were close to diesel. The B20 blend proved to be a better feedstock for usage in unmodified diesel engines with reduced tailpipe emissions. The aim of the work is an experimental evaluation of Chlorella emersonii biodiesel in a compression ignition engine.

MATERIALS AND METHODS

Biodiesel Production from Chlorella Emersonii Algae

In Figure 1, the biomass of Chlorella emersonii algae is collected manually and partially dried to remove water content. Then the entire biomass is crushed. Next, it is

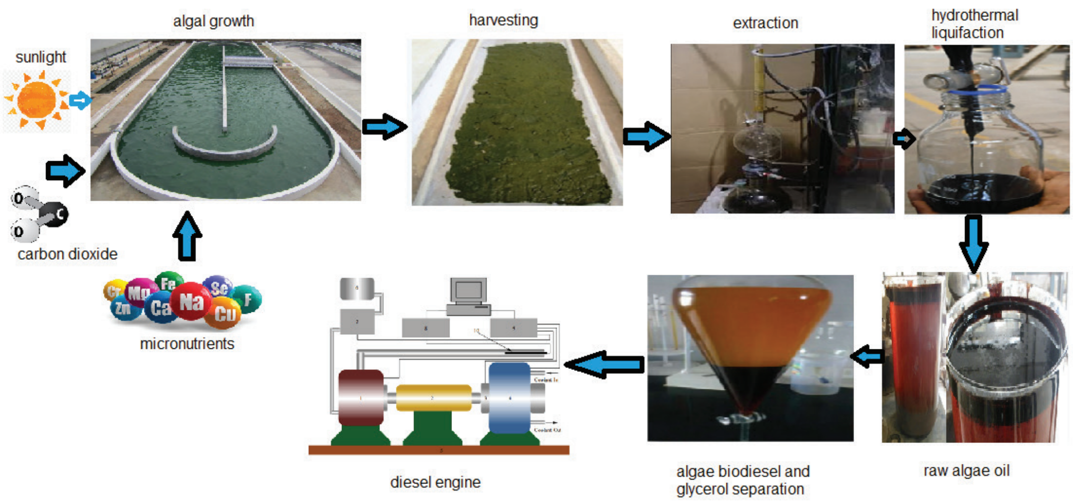

Figure 1. Preparation of *Chlorella emersonii* methyl ester (CEME).

Table 1. Annotations for Chlorelle emersonii methyl ester (CEME) fuel blends[10]

Sl. No.	Annotations	Descriptions
1.	D100	100% Diesel fuel
2.	B100	100% Chlorelleaemersonii methyl ester (CEME)
3.	B10	10% Chlorelleaemersonii methyl ester (CEME)+90% diesel
4.	B20	20% Chlorelleaemersonii methyl ester (CEME)+80% diesel
5.	B30	30% Chlorelleaemersonii methyl ester (CEME)+70% diesel

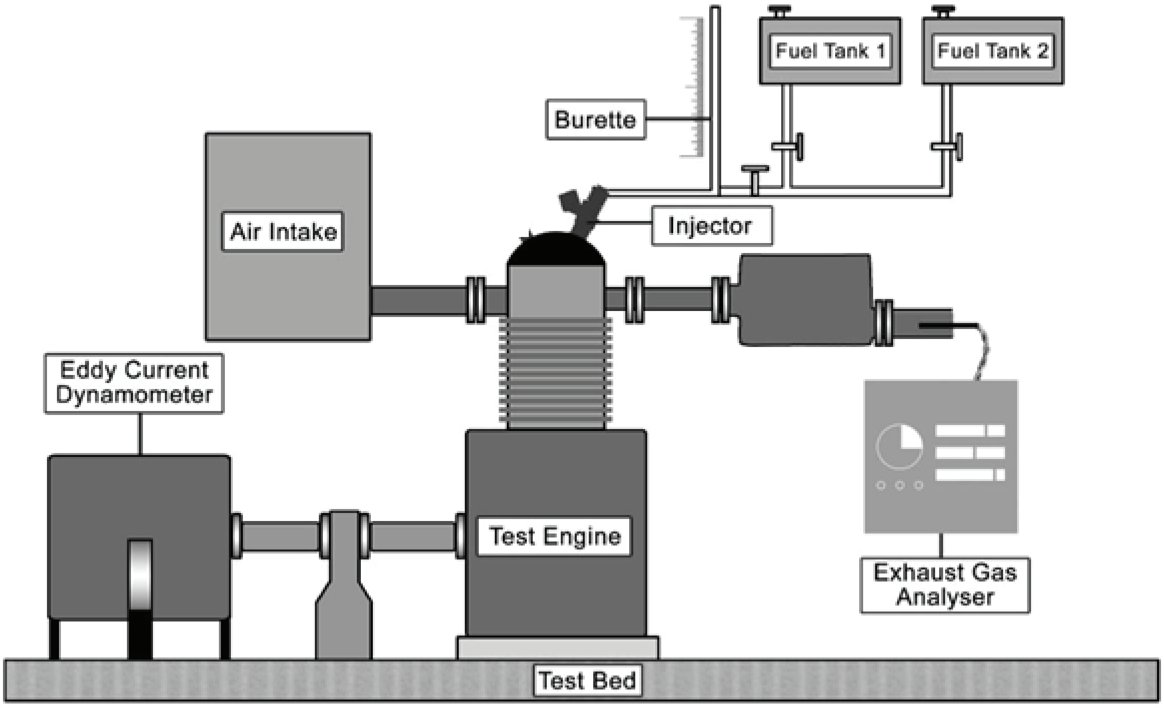

Figure 2. Layout of experimental setup.

allowed to dry for another 30 minutes to remove water content. Hydrothermal liquefaction is done to remove water content, and carboxylation is done to remove excess CO_2. This process is done by adding catalyst to biomass, heating it for a long time, and allowing it to settle for 24 hours. Finally, the biomass gets converted into Chlorella emersonii oil. Further, it is subjected to the transesterification process to remove triglycerides and reduce viscosity.

One-step transesterification is done to obtain Chlorella emersonii methyl ester (CEME). A potassium hydroxide (KOH) catalyst is used in this process to enhance yield quantity. Finally, the methyl ester and glycerin from triglycerides are separated, and CEME biodiesel is obtained. Impurities in biodiesels are separated by agitation with water, sedimentation, and separating. Thus, biodiesel without any impurities is obtained.

Experimental Setup

A single-cylinder, air-cooled, four-stroke, direct injection stationary research engine was employed for the current experiment. A number of gauges are connected to the engine to monitor fuel efficiency and other factors. The QRO-402 type exhaust gas analyzer is used to measure the levels of HC, CO, and NOx in exhaust gas. Using a smoke metre, the Avl437C detects smoke. Figure 2 depicts the full experimental setup.

RESULTS AND DISCUSSION

Performance Characteristics

Figure 3 indicates the variation of the BTE trend for all test fuel operated at full load conditions. It is clear that the BTE of the B30 blend of Chlorella emersonii methyl ester (CEME) is higher than other blends and is also close to diesel. It may be related to B30 fuel›s good combustion characteristics due to a higher cetane number, calorific value, oxygen content, and kinematic viscosity that made it burn effectively [11]. Hence, it exhibited a good result. Similar results were noted from Haik et al. [1], Subramani and Venu [12].

Brake Specific Fuel Consumption

A brake-specific fuel consumption measure is the amount of fuel and engine energy required to maintain a constant engine speed during brake applications. In general, fuel with a higher energy content (calorific value) is consumed less. From Figure 4, it is understood that the BSFC of the B30 blend is lower than other fuels and on par with diesel fuel. Brake thermal efficiency and brake-specific fuel consumption are inversely proportional to each other. Fuel with high thermal efficiency will exhibit lower fuel consumption [13]. Moreover, a higher calorific value with other good combustion qualities is attributed to a lower BSFC [14]. The results are also consistent with Subramani and Venu [12].

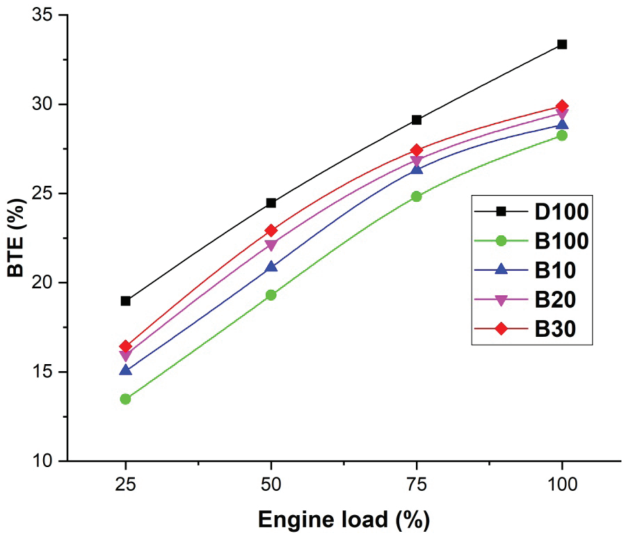

Figure 3. BTE vs engine load.

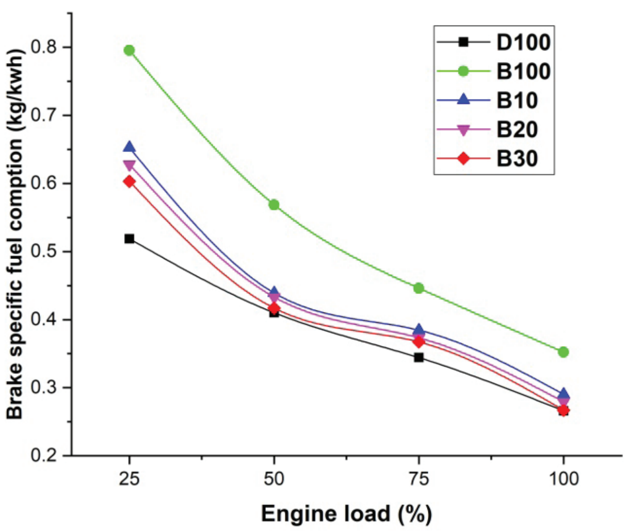

Figure 4. BSFC vs engine load.

Combustion Characteristics

Cylinder pressure

The cylinder pressure of fuel is one of the important parameters for analysing fuel combustion characteristics. The amount of fuel burned in premixed combustion hash determines maximum cylinder pressure. Viscosity, air-fuel mixture rate, and cetane index of fuel have a great influence on cylinder pressure. The evolution of cylinder pressure with varied crank angle at full load is seen in Figure

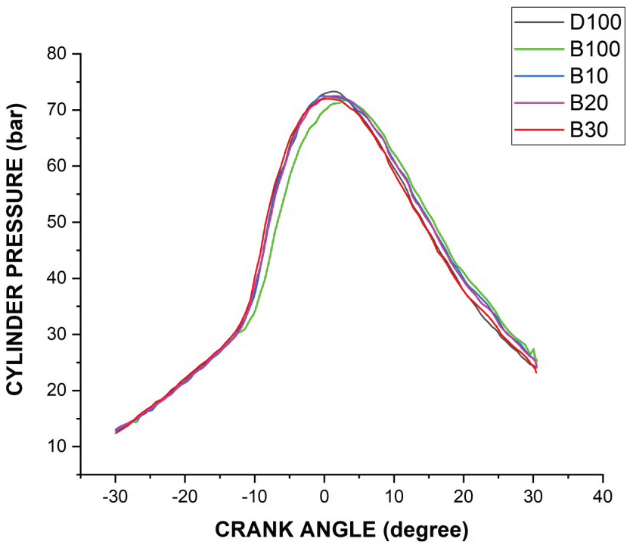

Figure 5. Pressure vs crank angle.

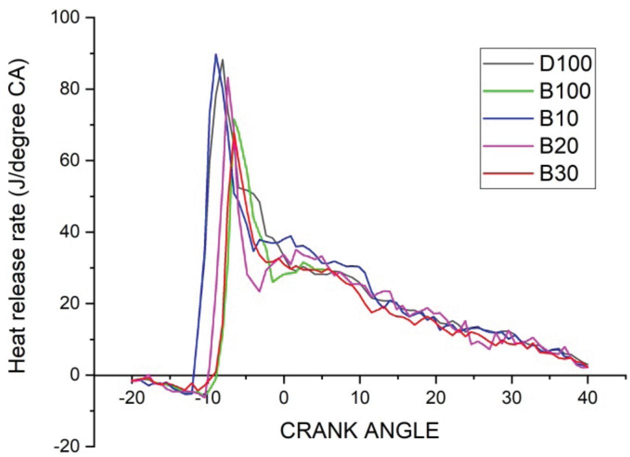

Figure 6. HRR vs crank angle.

5. It is evident from the graphic that nearly all fuels display similar pressure values. For the B10, B20, and B30 fuel blends of Chlorella emersonii biodiesel, high cylinder pressures of roughly 75 bar, 73 bar, and 72 bar, respectively, are recorded. According to Gumus et al. [15], calorific value and cetane number are important factors in peak pressure development. B10 demonstrated enhanced fuel properties such low kinematic viscosity, high cetane rating, and high calorific value that encouraged better burning. Good peak pressure is obtained for all fuel blends because of better fuel properties. Additionally, the presence of oxygen molecules in biodiesel supported a rise in line cylinder pressure. A similar result was observed by Haik et al. [1].

Heat release rate (HRR)

Fuel combustion characteristics, such as cetane number, calorific value, and flash point, affect how quickly heat is released. The correlation obtained from the thermodynamic law equation was used for finding the HRR value. Figure 6 shows the variation of HRR with respect to crank angle. The highest HRR of 90 J/°CA and reduced delay period were noted for the B10 blend of CEME, followed by diesel, B20, and B30 fuel blends. Because of the high viscosity and reduced density of B10, along with more fuel accumulation in the premixed combustion phase, a high HRR peak is obtained. Good combustion quality of all blends, especially B10 and B30, because of good cetane numbers and calorific values enabled fuel to burn well. Additionally, the presence of more oxygen content in fuel is attributed to complete burning and releasing more heat during the main phase of combustion [16].

Emission Characteristics

Hydrocarbon emission

Hydrocarbon emissions are one of the products of incomplete combustion. The major reason for the formation of hydrocarbons is the accumulation of fuel in the crevice volume of the injector, the nozzle passage, and the region between the cylinder and piston. Apart from these poor physical and chemical properties of fuel, such as high viscosity and poor combustion quality, fuel corroborates HC formation. It is carcinogenic and undesirable as it affects the haemoglobin in human blood. Here is an illustration of the trend graph of HC for varying load conditions in Figure 7. This observation shows that CEME's B30 blend emits less HC than other blends. Better viscosity of fuel has enabled it to form smaller fuel droplets, which has enabled it to burn well. Other factors, such as high O_2 content and cetane number, additionally improved the vaporisation character of fuel. enabled to form a better air-fuel mixture. Less rich mixture zones in the spray also paved the way for good combustion [17].

Carbon monoxide

Carbon monoxide is one of the products of incomplete combustion and is also referred to as regulated emissions. It is undesirable as it damages human tissues and causes other breathing issues and replaces oxygen in the blood. CO emissions are due to partial oxidation of fuel and the presence of more carbon in fuel. A high carbon-to-hydrogen ratio (C/H ratio) is expected to produce more CO. Figure 8 depicts the CO_2 emissions with respect to varying engine loads. It is clear from the figure that B30 produces less CO. At low load conditions, the emission was high, and a reduced trend is obtained with increasing load conditions. Better oxidation characteristics, along with the presence of naturally available oxygen molecules in fuel B30, supported complete oxidation. Other qualities such as low viscosity, superior small droplet size, and high cetane number support better

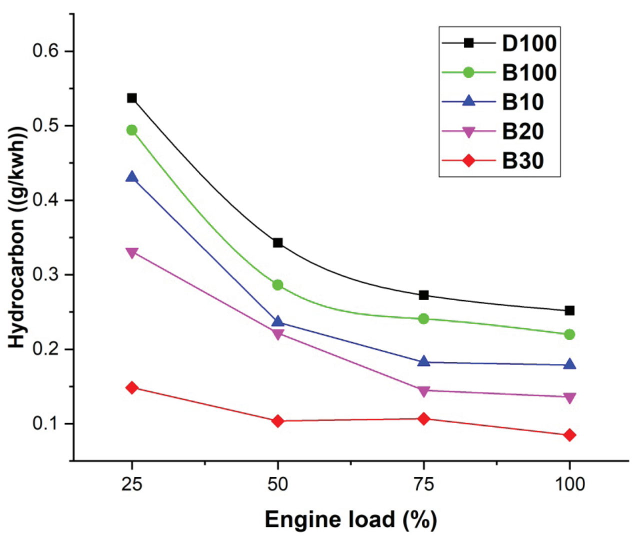

Figure 7. Hydrocarbon vs engine load.

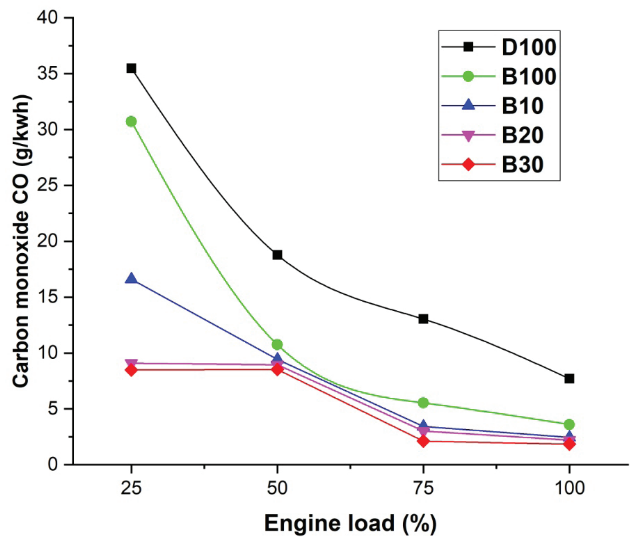

Figure 8. Carbon monoxide vs engine load.

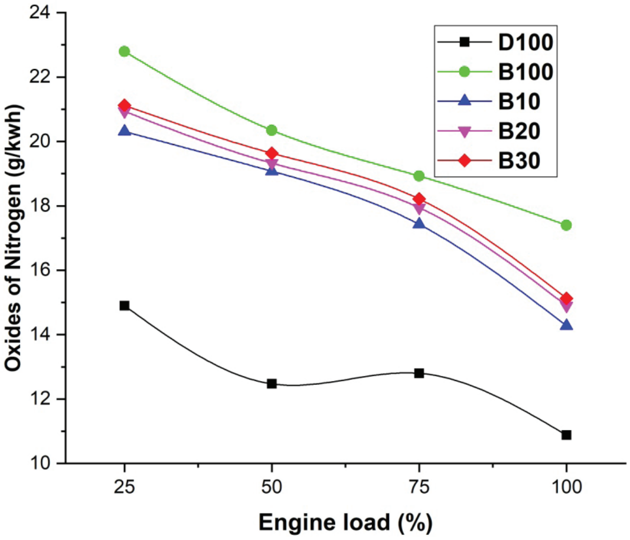

Figure 9. Oxides of nitrogen vs engine load.

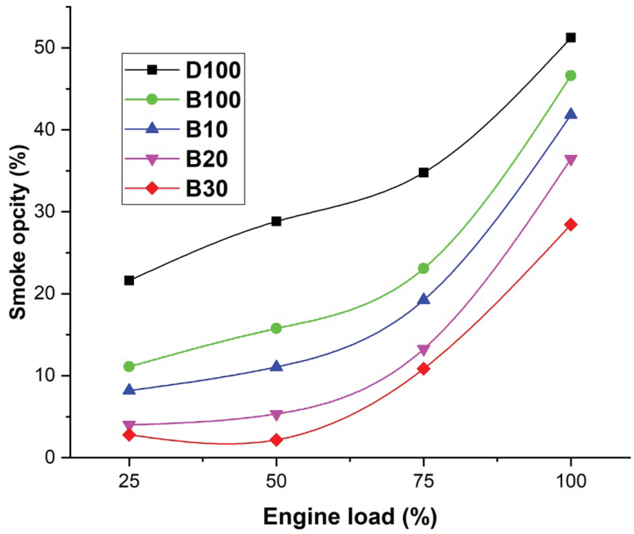

Figure 10. Smoke vs engine load.

burning of fuel at full load conditions because of the high cylinder temperature that enables it to burn completely. Thus, low emissions of carbon monoxide are noted for all fuel blends [18]. Similar carbon monoxide emission output was noted by Jayaraman et al. [8], Subramani and Venu [12] from their studies.

Oxides of nitrogen

An oxide of nitrogen is a product of complete combustion and is also referred to as a regulated emission. It is formed due to the oxidation of nitrogen present in the air. This oxidation occurs at high cylinder pressure, i.e., about 1500 °C. NOx is undesirable as it is responsible for acid rain. Engines operating at stoichiometric conditions for long periods of time experience rises in cylinder temperature, thus enabling N2 and O2 inside the cylinder to form NOx. NOx is plotted against engine load in Figure 9. In figure B100, high NOx is shown, followed by B30 and B20. It may be that B100 has inferior properties like high viscosity and cetane number, but NOx is high since it contains more oxygen molecules than any other fuel blend, resulting in high NOx formation at higher cylinder temperatures. B30 showed less NOx than B100 but higher than diesel, B10, and B20. High oxygen content, along with high fuel density, has caused fuel to burn better and a rising combustion temperature. Improved rate of combustion because of a good cetane number also supported the fuel's ability to operate in stoichiometric conditions. Hence, high NOx is obtained. Other blends possess less oxygen than B100 and B30, and inferior combustion quality leads to lower NOX emissions [19]. Thus, B30 was claimed to be the optimum blend from a NOx emission point of view. These results are analogous to those of the experiment conducted by Makareviciene et al [6].

Smoke

Smoke is a visible emission and is solid carbon that comes out of the engine without involving combustion or oxidation. It is also undesirable to humans as it affects the eyes and causes lung and breathing disorders. Figure 10 depicts the trend of smoke formation at various engine loads. During different combustions, the fuel droplets splintered into small carbon particles, which then got oxidised in the combustion zone. Poor atomization, a higher C/H ratio, high viscosity, and rich zone formation are some of the other reasons for smoke formation. Thus, the B30 blend exhibited reduced smoke emissions compared to other fuels. Because of better fuel combustion characteristics along with other good physical and chemical properties [20]. Similar smoke results were noted from Haik et al. [1] and Gourari et al. [21]

Table 2. Physico-chemical properties of the CEME

S.NO	Properties	Result	Method	SNI
1	Specific Gravity	0.8574	ASTM D1293	0.840-0.900
2	Kinematics Viscosity	9.1247	IKU/5.2/TK-03	2.5-6.5
3	Flash Point	144	IKU/5.2/TK-04	Min 99
4	Fire Point	10	IKU/5.2/TK-05	10-15
5	Water Content	trace	ASTM D 98	Makes, 0.05

CONCLUSION

This study investigated the use of fuel obtained from algae, Chlorella emersonii, as an alternative fuel for diesel engines. In addition, experiments were conducted in order to improve results. It was transesterified to reduce fuel viscosity to prevent scuffing of piston rings, clogging of fuel injectors, and vaporization. Many literature studies have shown good results for fuel with low viscosity. This motivated me to carry out the present work. Initially, fuel and additives in a fuel strategy were adopted and their results compared. Thus, from these outcomes, the best fuel was identified and used for other experiments with engine modification techniques to improve CEME results.

- As a result of the experiment, the B30 blend of CEME was found to be a more efficient and effective fuel in terms of combustion, emissions, and performance.
- There was also an improvement in efficiency and fuel consumption. By increasing nitrogen oxides, a number of emissions are reduced, including hydrocarbons, carbon monoxide, and smoke.
- There was also an improvement in cylinder pressure and heat release rate. Therefore, the first experiment suggests that B30 is the better and most promising fuel.

Further research on the low heat rejection (LHR) strategy can be implemented with Chlorella emersonii biodiesel and other nanoadditives such as cerium nanoadditives, carbon nanotubes, titanium oxide, and other antioxidants.

NOMENCLATURE

CI	Compression ignition
N_2	Nitrogen oxides
CO_2	Carbon dioxide (CO_2),
H_2O	Water
O_2	Oxygen
HC	Hydrocarbon (HC)
NOx	Oxides of nitrogen
CO	carbon monoxide

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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