Research Article

Comparative performance and emission studies of the CI engine with Nodularia Spumigena microalgae biodiesel versus different vegetable oil derived biodiesel

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Abstract

Biodiesel is a renewable diesel fuel that can be burned in any unmodified diesel engine at any concentration. Biodiesel from Nodularia Spumigena microalgae produced by transesterification is used in the present study. Methyl esters of algae have been prepared after successful extraction of biomass in an open pond cultivation system. Biodiesel was blended with diesel fuel with the volumetric ratios of 10% (A10) and 20% (A20). The experiments were conducted on a constant speed (1500 rpm), 4-stroke diesel engine fitted with diesel particulate filter (DPF) at a fuel injection pressure of 180 bar. Methyl esters of Karanja oil, Rice Bran oil, and Castor oil were also tested in the same engine for comparison. BSFC values increased with increase in Biodiesel blend percentage in diesel. However, K20 and A20 showed fuel economy by 5.51% and 10.06% in comparison to diesel. The emissions of CO and HC with fuel A20 are decreased by 65.77% and 53.33% respectively. The NOx emission showed an increasing trend with the blending of algae methyl esters in diesel. The presence of DPF is credited for significant reduction of PM emissions. The results predicted that the usage of algae blends could be supported, although there is a slight reduction in engine performance and an increase in NOx emissions.

Keywords Biodiesel blends · Nodularia Spumigena microalgae · Engine performance · DPF · Exhaust emissions

List of symbols

BSFC	Brake specific fuel consumption (kg/kw h)
DPF	Diesel particulate filter
CO	Carbon monoxide (%Volume)
BTE	Brake thermal efficiency (%)
HC	Hydrocarbons (PPM)
NOx	Emissions of nitrogen (PPM)
DI	Direct ignition
CA	Crank angle (°)
CV	Calorific value (kJ/kg)
η_v	Volumetric efficiency (%)
SOC	Start of combustion
E_a	Activation energy
CN	Cetane number
T_{TC}	Charge temperature
T_i	Initial temperature
r_c	Compression ratio
P_{TC}	Charge pressure
SOI	Start of ignition
EEA	European environment agency
KME	Karanja methyl ester
AME	Algae methyl ester
RME	Rice bran methyl ester
CME	Castor methyl ester

1 Introduction

Currently, global warming is one of the world's biggest challenge. It has also contributed to unprecedented climate change, extirpated fuels and fossil energy supplies [1–3]. The use of diesel engines has been expanded

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globally as a consequence of rapid industrialisation [4]. The rise in amounts of nitrogen oxide (NOx) and PM emissions have created serious climatic and health complications [5]. There is a need for safe and sustainable alternative resources for the production of energy [6–8]. Efforts of Researchers came out as the implementation of Biodiesels as a source to present engines to mitigate the ill effects of fossil fuels like diesel. Biodiesel is one such option which has properties close to diesel fuel [9–19]. This biodiesel, however, has the disadvantage of high viscosity and a lower heating value compared to neat Diesel [20]. The high viscosity of Biodiesel prevents its use directly in the DI engine as it triggers clogging of the injector and more considerable deposits in the cylinder [21, 22]. Many efforts were in place to produce a neat alternative to diesel fitting the other renewable and environmental needs. The continuous efforts are needed to get the benefits of the fuel-based alternative for future generations of humankind. Present work is aligned with the ongoing research such as identification of new kinds of feedstocks to convert them into biofuels for use in the present engines.

1.1 Literature review

Biodiesel is a vegetable oil-based fuel containing long-chain alkyl methyl esters. The method of making biodiesel from raw biological stock is known as transesterification [23–26]. The classification of biodiesel is generally made based on feedstock origin. The first generation Biodiesel produced from food crops, that is, edible biomass, such as wheat, barley, corn, coconut and sunflower [27]. Food sources are likely to be unsuitable owing to their base price and process of production [28–30]. The second-generation Biodiesel was synthesised from non-food crops, for example, Lignocellulosic material, Cassava, Jatropha, Miscanthus grass and several other organic species [29]. These crops require vast moist soil lands, and this made them difficult to cultivate. Third generation sources are aquatic biomasses such as algae [31, 32].

Algal are forms of aquatic plants with smooth stems with size variations from small to the meter in length. Growth of algae takes place because of Photosynthesis, algae stores the lipids as Tri Acyl Glycerides (TAG's). Biomass can be extracted from the optimal process, which is further converted to biodiesel through transesterification [33–40]. The amount of biomass to biodiesel conversion is meagre, owing to fewer quantities of biomass extracted from extensive quantity collection of algae source. The production of large quantities algae is, however possible in lakes (environment) rich in nitrogen to phosphorous ratio (N/P) with less cost of investment [41–43]. Algal are generally microalgae with size is less than 0.4 mm in diameter. Three distinct kinds of algae are present viz. diatoms, green algae and golden algae. The microalgae yield fatty acids and lipids from their biological processes. The lipids are useful in storing energy in their cells [44]. Microalgae gained the attention for the production of Biodiesel due to an inflated production rate and large lipid yield nearly equal to 50–70% [45]. Biodiesel still is not economically competitive with diesel, taking into account of on-going research the studies on various algal organisms is appropriate for the use of algae in the current engines [41, 46–50]. The authors have been motivated by the collected literature and aimed at working on making algae-based biodiesel as a substitute for diesel fuel.

The present work deals with the conversion of Nodularia Spumigena algae into biomass, followed by its use in a diesel engine. The methyl esters of selected algae have been obtained through transesterification. Cultivation and growth of algae took place in both photo-bioreactor, followed by an open pond system. For comparison, the methyl esters of Karanja oil, Rice Brawn oil, and castor oil has were prepared and used for testing. The properties of these fuels are shown in Table 1. It was observed that the initial growth of pure Nodularia algae was slow in photo-bioreactor. However, the higher and considerable yield rates of mass were observed through an open pond system. The general parametric optimization techniques

Table 1 The properties of the test fuels

Properties	Unit	Diesel	KME	AME	RME	CME
Density@25 °C	Kg/m^3 (ASTMD 1298)	830	885	795	889.9	978
CV	kJ/kg (ASTM D420)	43,200	40,758	37,506	37,081	36,160
Viscosity@40 °C	cST (ASTM D445)	2.78	5.12	4.84	5.45	2.40
Flash Point	°C (ASTM D93)	76	161	130	124	235
Pour Point	°C (ASTM D97)	3.11	5.12	−2	−9	−4
Cetane value	–(ASTM D613)	47	56.65	45	46	41
Sulfur content	% w/w(ASME-0.0015)	0.012	0.002	0.080	0.009	0.013
Water content	%w/w(ASTM-0.05 (max))	0.0040	0.005	0.017	0.028	0.03
Cloud point	°C (ASTM D-2500)	−3 to 12	6	4	7	8
Ash content	% w/w(ASTM < 0.02)	< 0.01	0.005	0.017	0.012	0.023

were followed during the cultivation and extraction of algal biomass. The biomass extraction methods used have been natural and safe in the view of the current climatic conditions. The algae stains of good quantities have been collected from the geographical location of Guntur district (16.24 N 80.56 E), Andhra Pradesh, India.

2 The experimental setup and procedure

A single-cylinder 4-stroke direct ignition (DI) Diesel engine was selected. The engine was operated at a fixed speed of 1500 rpm throughout the tests. The reason behind the selection of these engines is the interest of farmers to produce power with local bio-diesels in rural India. The schematic picture of the engine is presented in Fig. 1. The information on the engine is given in Table 2. The fuel injection pressure has been used of 180 bar, and the experiments carried out at different loads. From the previous observations, it is found that with an increase in the injection pressure, the engine performance slightly improves, however, the present tests are conducted at an injection pressure of 180 bar (The manufacturer's suggestion) to ensure the better comparison of biodiesel mixtures with diesel. Generally blends of 20%, 10% are widely used by researchers and in this work to it was considered only 10%, 20% because mixing of biodiesel quantities higher than 20% leads to clogging of the fuel injector. The engine has the facility to use Diesel Particulate Filter (DPF), and the tests are conducted with and without DPF. The DPF is added to reduce PM emissions from the engine exhaust. The fuel injection pressure has been selected as 180 bar since the engine uses blends of biodiesel and diesel. However, the higher injection pressures also can be used to improve the performance of spray, which is less effective with biodiesel blends. The experiments were performed as constant speed variable load tests. The exhaust emissions of the engine were measured using an AVL gas analyzer. The technical details on the gas analyzer are shown in Table 3.

Table 2 The Test Engine Specifications

Engine	Kirloskar, Single-Cylinder, Four-stroke, Constant Speed – 1500 RPM, Stroke 110.00(mm), Bore 87.50(mm), Swept volume 661.45 (cc), Water Cooled, Compression Ratio 17.50
Propeller Shaft	With universal joints
Fuel Tank	15 lit Capacity with glass fuel calibration column
Air Box	Orifice meter and Manometer (MS fabricated)
Temperature indicators	Digital, multichannel with selector switch
Temperature Sensors	Thermocouple, Type K
Dynamometer	Type Eddy Current

Table 3 The standards of exhaust gas analyser

Parameter	Manufacture	Value	Method of measurement
NOx	AVL	PPM	Chemiluminescent
HC	AVL	PPM	FID
CO	AVL	%Volume	NDIR
Smoke	AVL	Percentage	Opacity

Table 4 describes the uncertainty values of the instruments used in the present experimental work. The overall percentage of the uncertainties of this experiment has been determined using the calculation to the square root of the uncertainty of TFC, BP, BSFC, BTE, CO_2, HC,

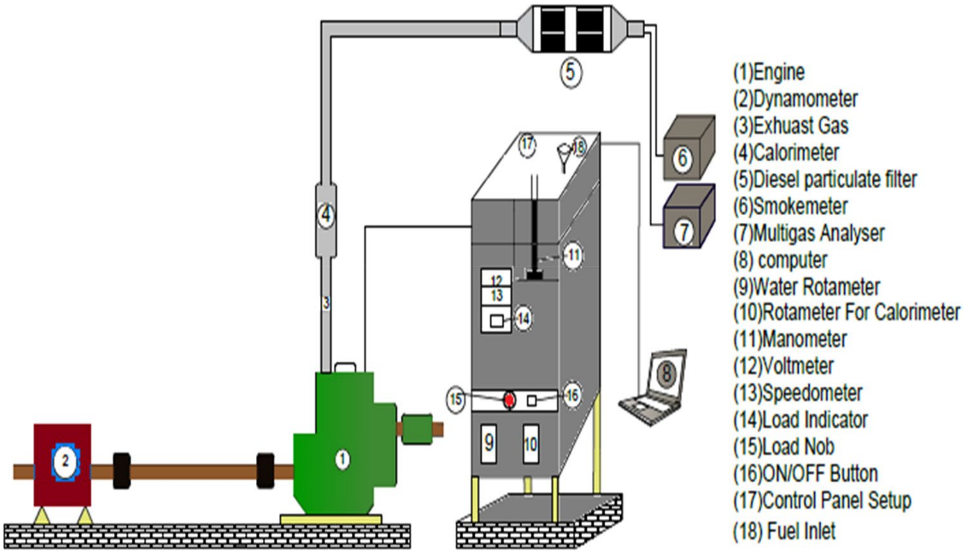

Fig. 1 Schematic view of experimental engine

Table 4 The list of instruments with given values of uncertainties

Instruments	Accuracy	Range	%uncertainties
Gas analyser	± 0.03%	CO 0–10%	± 0.2
	± 0.03%	CO_2 0–20%	± 0.13
	± 15 ppm	HC 0–20,000 ppm	± 0.2
	± 20 ppm	NOx 0–5000 ppm	± 0.2
Smoke meter	± 0.2	HSU 0–100	± 1.0
Temperature indicator	± 1 °C	0–1200 °C	± 0.12
Stopwatch (digital)	± 0.2 s	–	± 0.2
Pressure sensor	± 1 bar	0–110 bar	± 0.1
Crank angle encoder	± 1°	–	± 0.2
Speed sensor (proximity type)	± 10 rpm	0–9999 rpm	± 1.0
Torque indicator	± 0.1 N m	0–100 Nm	± 0.2
Fuel flow rate indicator(digital)	± 0.02 kg/h	0–999 kg/h	± 0.13

NOx, Smoke Number, EGT, the total percentage of pressure [51].

The total percentage of uncertainties = $\sqrt{\{(0.1)^2 + (0.2)^2 + (0.1)^2 + (1)^2 + (0.2)^2 + (0.1)^2 + (0.2)^2 + (0.2)^2 + (1.0)^2 + (0.15)^2 + (1.0)^2\}} = \pm 2\%$. The total share of uncertainty equals to ± 2% with the different instrumentation, testing methods and the methodology adopted in this empirical work.

3 Results

The tests were carried out for testing diesel and bio-diesel performance and emission characteristics. The blend of 10% Karanja vegetable oil methyl ester with diesel is denoted as K10, and 20% is denoted as K20. Similarly, the other fuels are indicated, for example, algae methyl ester 10%, 20% with diesel as A10, A20, Rice brawn oil methyl ester 10%, 20% with diesel as R10, R20 and Castor oil 10%, 20% with diesel as C10, C20 respectively.

3.1 Brake thermal efficiency (BTE)

BTE defines the heat energy proportion of the fuel converted into useful work, i.e. break power (BP). The results are shown in Fig. 2. BTE increases with load percentage, and all the fuels have shown a similar trend. The Blends of biodiesel and diesel showed lower values vowing to the fact of reduced calorific value. However, it can be demonstrated that biodiesel blends can successfully manage the loss of energy due to blending if used on long intervals of time. BTE of diesel is 26.67% and the blends values 6.7%, 0.95%, 7.82%, 2.01%, 8.6%, 3.02%, 9.61%, and 4.82%. It can be noted that K20 and A20 shown the best results.

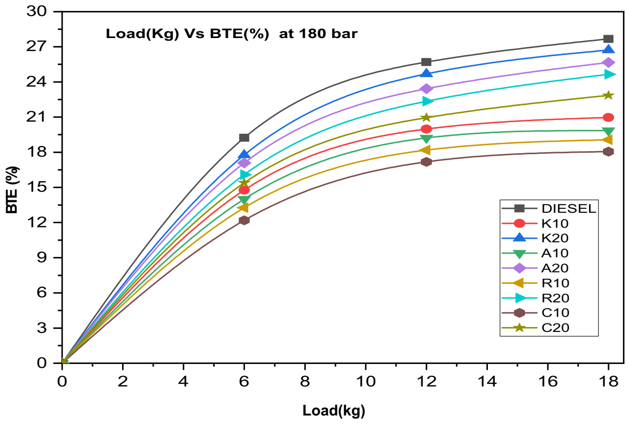

Fig. 2 Load versus BTE variations

3.2 Brake specific fuel consumption

The contrast of BSFC with the load is shown in Fig. 3. The trends of BTE can be correlated for understanding the fuel consumption patterns with different fuels. The BSFC decreases with the load till 12 kg and then maintained the same values with the further increase of the load. The downsizing of the engines is only possible with fuels of higher calorific values, yet biodiesel suffers in this point due to its high fuel consumption when its percentage increases in a blend. The obtained BSFC values in Kg/KW h are 0.308, 0.376, 0325, 0.398, 0.339, 0.418, 0.411 and 0.359 respectively. Here K20 and A20 are comparable with neat Diesel.

3.3 Volumetric efficiency (η_v)

The trends of variation of η_v with load are displayed in Fig. 4. The volumetric efficiency decreases with the increase of load, as shown in the figure, due to the

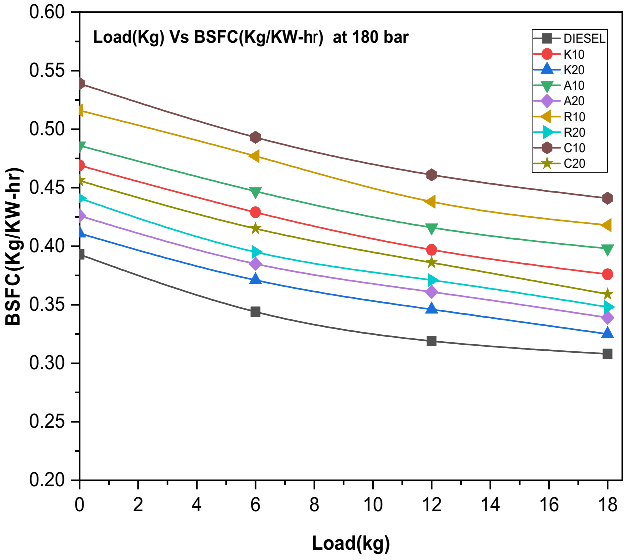

Fig. 3 The load versus BSFC variations for different biodiesel mixtures for different biodiesel mixtures

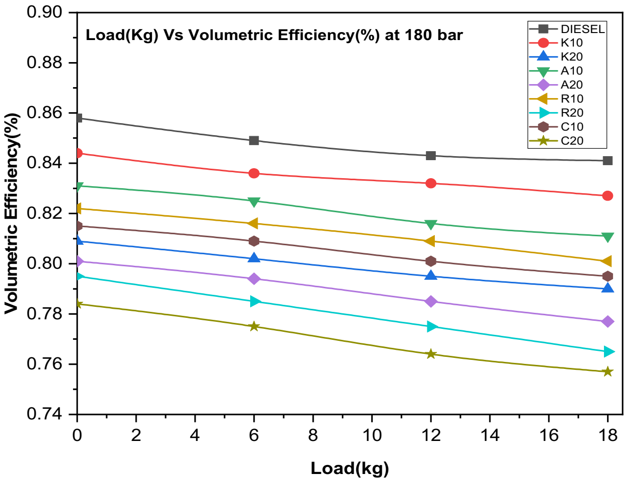

Fig. 4 The variations of volumetric efficiency with variations of load for different biodiesel mixtures

mixing of fresh air with unburnt gases. The η_v relay on the density of the gas in the cylinder, with the increase of temperature. Blends often show lower density due to the problem of mixture strength variation. There is no significant observation about drastic changes in density when the engine run with selected fuels. The volumetric efficiency for diesel and its blends K10, K20, A10, A20, R10, R20, C10, C20 are 84%, 82%, 79%, 81%, 77%, 80%, 76%, 79% and 75% respectively at maximum load condition.

3.4 Emissions of carbon monoxide

Figure 5 illustrates the distinction of emissions of carbon monoxide with the load for cases (a) without DPF and (b) with DPF. Despite rising loads of biodiesel mixtures, the level of CO decreases. The emissions of CO followed the diminishing trend with the increase of the engine load. The emissions of CO are considerably reduced with the rise of biodiesel percentage in diesel. This is true for all blends, including A10, A20. At the maximum load, CO emissions are 0.26%, 0.13%, 0.035%, 0.15%, 0.068%, 0.18%, 0.19%, 0.22% and 0.109% respectively. While using DPF the values are 0.101%, 0.026%, 0.105%, 0.042%, 0.119%, 0.061%, 0.139% and 0.079% respectively. The reason assigned is effective oxidation.

3.5 Emissions of hydrocarbon

The emissions of HC with the load variation presented in the Fig. 6 for cases (a) without DPF and (b) with DPF.

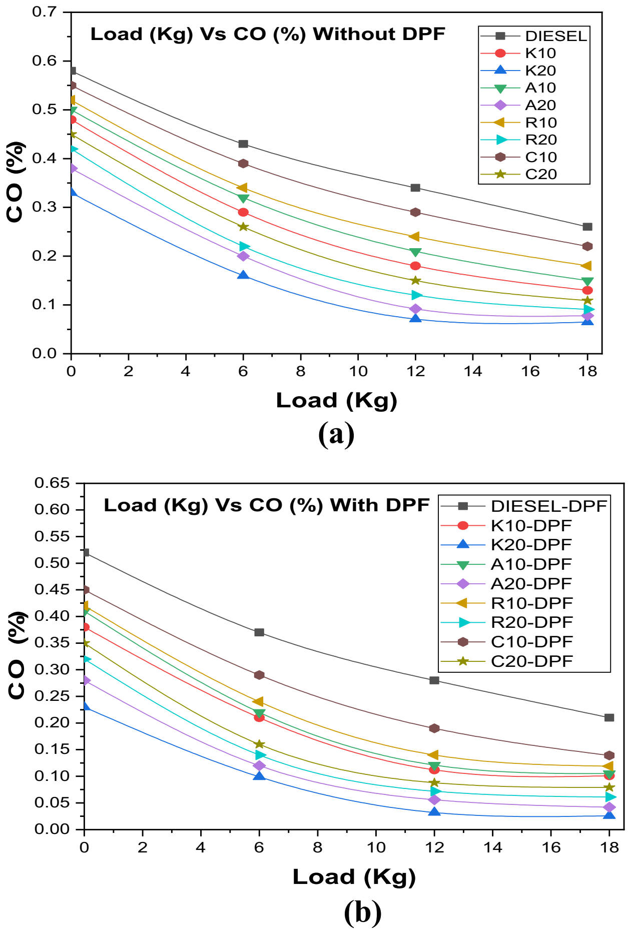

Fig. 5 The emissions of carbon monoxide with a variety of load for different biodiesel mixtures (**a**) without and (**b**) with DPF

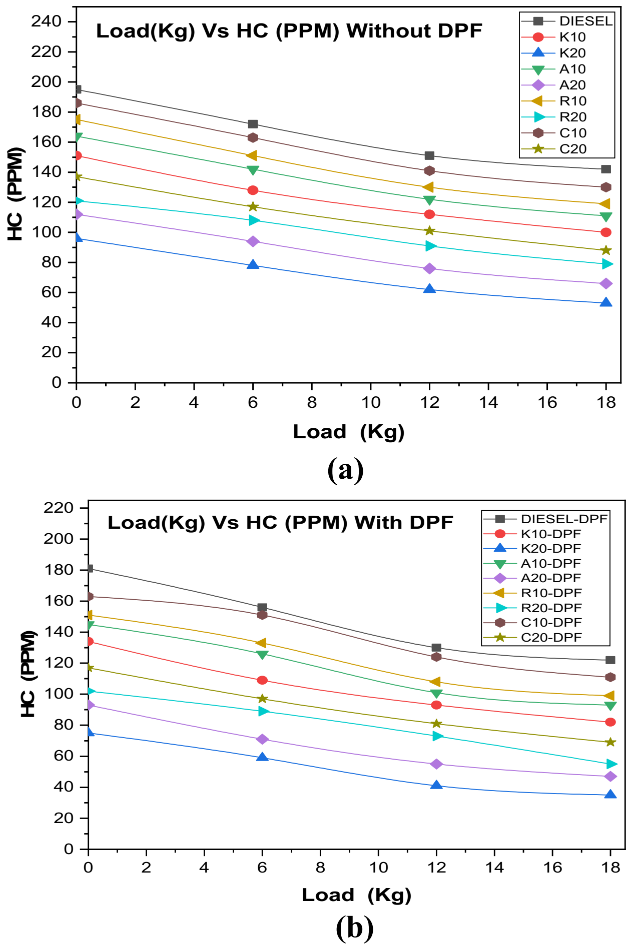

Fig. 6 Variations of hydro-carbon emissions with the load for different biodiesel mixtures (**a**) without and (**b**) with DPF

With the increasing load, a substantial reduction in the HC emission found with an increasing blend ratio from 0 to 20% of KME, AME, RME and CME blends. At maximum load condition, the emissions of HC for diesel and 20% biodiesel blends are 142 ppm, 100 ppm, 53 ppm, 111 ppm, 66 ppm, 119 ppm, 79 ppm, 130 ppm and 88 ppm, respectively. The reductions of HC emissions for biodiesel blends are indicating better combustion. With DPF, the values reduced with the increase in load for all blends. The values for above-said blends with DPF at full load are 82 ppm, 35 ppm, 93 ppm, 47 ppm, 99 ppm, 55 ppm, 111 ppm and 69 ppm respectively.

3.6 Emissions of NOx

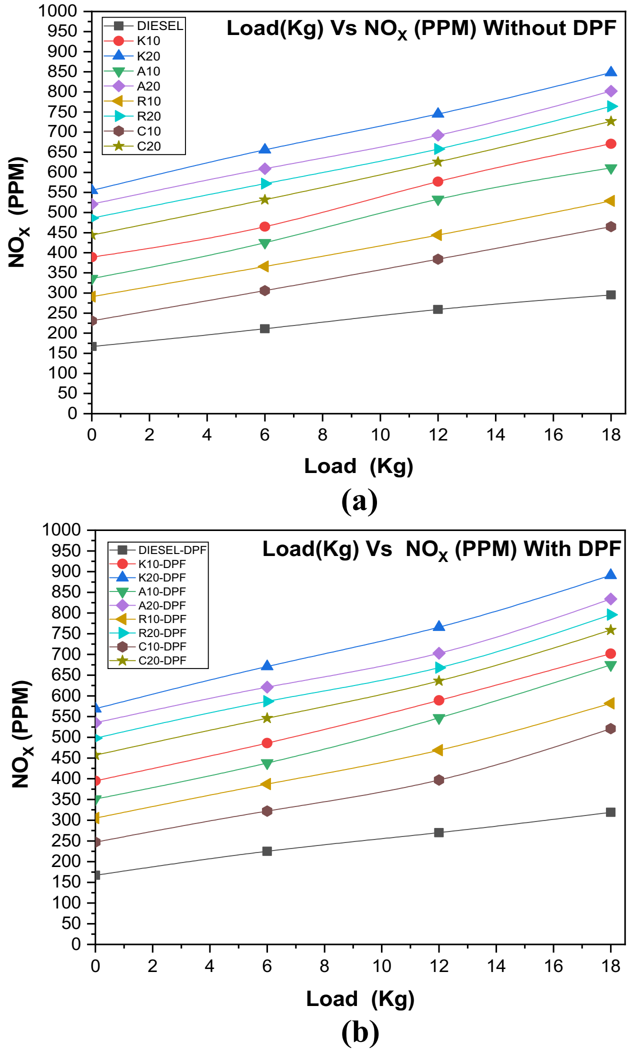

Fig. 7 Plots of the NOx emissions versus load for different biodiesel mixtures (**a**) without and (**b**) with DPF

The trends of NOx emissions for all the fuels shown in Fig. 7. At the maximum load, NOx emissions are higher. The NOx emissions are of serious concern in combustion systems since the emissions are due to high temperature. The mitigation of NOx is not possible by the usage of biofuels since there is no possibility of equivalent absorption of the same by the increased cultivation of vegetation or other sources. However, the use of algal biodiesel blends results in a slight increase in NOx emissions. At the maximum load, the values are 295 ppm, 671 ppm, 848 ppm, 611 ppm, 802 ppm, 529 ppm, 764 ppm, and 727 ppm without DPF and with DPF these values are 319 ppm, 702 ppm, 891 ppm, 675 ppm, 834 ppm, 582 ppm, 796 ppm, 521 ppm, 729 ppm. Because of the complete combustion of oxygen content in the plant oil, increases cylinder temperature.

3.7 Cylinder pressure

Figure 8 represents the disparity of the cylinder pressure with the crank angle at the full load. A peak value of pressure obtained for diesel at the full load is 58.97 bar which occurred at a 378° crank angle. The peak values obtained

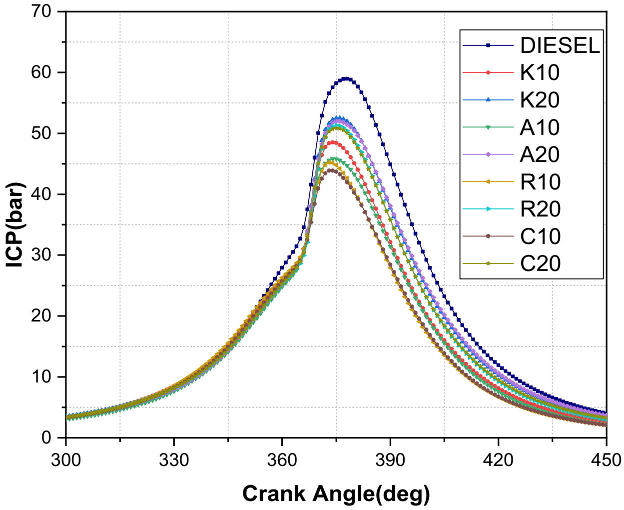

Fig. 8 The variation of in-cylinder pressures

for K20, A20, R20 and C20 are 52.53, 51.99, 51.32 and 50.86 bar at 376, 376.1, 375.4, and 375° respectively.

3.8 Net heat release rate

The heat release rate versus load (the full load) is presented in Fig. 9. Start of the ignition indicated by a steep rise which is in the first part of the graph. After the delay, the premixed phase with rapid combustion showed that air–fuel burns fast and to reach controlled combustion. The maximum heat of 59.56 J is released at a 367° crank angle for Diesel at the full load.

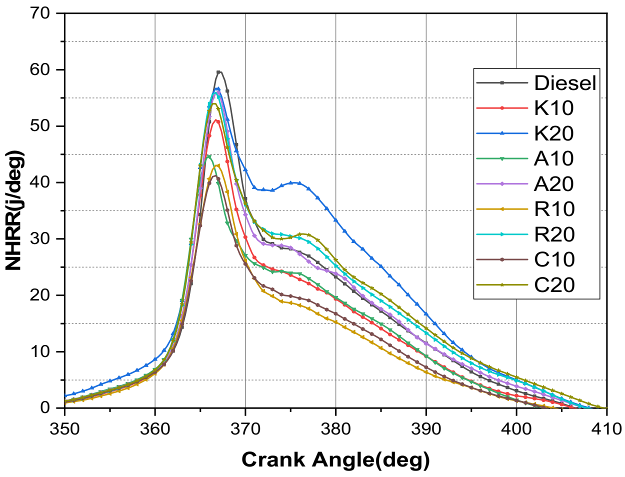

Fig. 9 The net heat release rate variation with the crank revolution for the tested the crank angle for the different fuels tested blends of Diesel and pure Diesel

3.9 Ignition delay

Figure 10 presents the comparison of ignition delay values of different fuels. The ignition delay period is the time gap between the SOI and the SOC. Physical factors affecting delay are spraying formation, pressure and the temperature of charge. SOC has been noticed from the plot of cylinder pressure data. The appropriate relations have been used to estimate the ignition delay, which is shown below. The activation energy (E_a) derived for each blend based on the Cetane number.

$$E_a = \frac{618,840}{CN + 25} T_{TC} = T_i r_c^{n-1} \quad P_{TC} = P_i r_c^{n}$$

For the fuels Diesel, A20, K20, C20, R20 and C10, the ignition delay has been estimated in milliseconds as 0.375, 0.415, 0.36, 0.375, 0.355 and 0.37 respectively.

4 Discussion

The motivation of work is taken from the concept of 'creation of sustainable and renewable sources of energy'. The present work links with the usage of available feedstocks to produce the biodiesel as per standards of ASTM. Many of the previous works have shown the methods for effective utilisation of biodiesel in diesel engines. The results of this work can be beneficial towards the exploration of local algal stocks for making of biodiesel. Similar works are being carried out by prospective authors focussing on the method of transesterification, growth characteristics

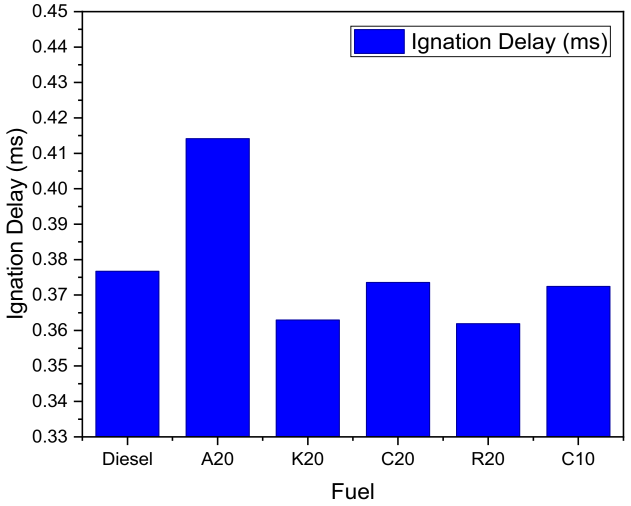

Fig. 10 Ignition delay in terms of crank angle for the diesel and blends

of algal biomass, and evaluation of engine combustion parameters. The scope of the selected work and the methodologies adopted are in line with the quality works of previous researchers. There is a need for continuous exploration of available algal feedstocks which can be the best options for the next generations. Commercialization aspects can be considered once the fuel production with economised price and quality are ensured.

5 Conclusions

The performance, emission characteristics of a single-cylinder 4-stroke DI diesel engine operated with diesel, biodiesel blends were investigated, and the findings of the experiments as follow.

1. The fuel blends K20 and A20 showed better combustion efficiency as they are comparable with diesel.
2. BSFC values of K20 and A20 low by 5.51% and 10.06% in comparison to Diesel, whereas other blends have shown increased values of BSFC.
3. The Volumetric efficiency (η_v) decreases with the increase in load. The maximum value is obtained for Diesel, and the minimum value is with C20, which are 84% and 75% respectively.
4. The CO emissions are found to be reduced with the increase of load. At the full load, K20 and A20 are found to have fewer values.
5. The HC emissions are reduced with blends of biodiesel, and the value is 47 ppm for blend A20.
6. NOx emissions are high with algae and other plant-based biodiesel.

In conclusion, the emissions of CO and HC for biodiesel blends have been high, with a slight increase in NOx emission levels. The maximum NOx emission levels identified to be 891 ppm and 834 ppm for K20 and A20 with DPF for the value of 319 ppm of diesel fuel. K20 and A20 Biodiesel blends showed optimal performance in the complete testing for performance and emission characteristics. The selected locally available algae to stain Nodularia Spumigena biodiesel blends A10 and A20 can be used in diesel engines.

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Compliance with ethical standards

Conflict of interest The authors do not have any conflict of interest.

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