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Article

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Research paper

Experimental investigation on performance, combustion and emission characteristics of DI diesel engine using algae as a biodiesel



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ABSTRACT

Diesel Powered engines are predominately used in transport and power generators. Due to rapid depletion of fossils fuels like diesel, there is need to find alternate resources for as a fuel for transport and power sector. The use of third generation fuels like algae seems to be a promising solution to satisfy our energy demands in future. In these work algae is used as an alternative fuel with different blend combination with diesel and the results obtained are summarized. Algae fuel is blended with diesel on a volume basis, namely A10, A20, A30, A40 and A100 and made to run in diesel engines. The properties of the fuels were found according to American Society for Testing and Materials standards. Experimental testing was carried out in a single cylinder direct injection diesel engine. Among the various blends tested A20 shows closer estimation with diesel results in higher thermal efficiency lower HC, CO, Smoke and particulate matter emissions. However, the other emissions like Nitrous oxide and carbon dioxide were shown marginally higher. Regarding cylinder pressure and heat release rate curves, the peak value obtained is considerably lower at higher load condition while compared with diesel.

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1. Introduction

Energy demand is rapidly increasing day by day in the world and it is expected to increase about 60% by the year 2035 (Outlook, 2010; Chen et al., 2011; Karavalakis et al., 2009). The increase in energy consumption caused depletion of fossil fuel and if this scenario continues further, resources like oil, natural gas and coal will not extinct in about 40 years, 55 years, and 130 years respectively (Nautiyal et al., 2014). Due to the increasing fuel consumption per capita the fuel prices also increasing day by day. Over the past two decade, many research was carried out in the utilization of biofuel for I.C engines (Tsaousis et al., 2014; Al-lwayzy and Yusaf, 2017). It was also estimated that there is about 1.1% rise in energy consumption in transportation sector is observed globally every year (Mofijur et al., 2015). Biofuels are alternate fuels usually obtained from bio mass (Chisti, 2007). The main source of biomass is their feedstock which includes crop, residues, forest residues, and municipal waste etc (Mofijur et al., 2013; Song et al., 2008). The bio fuel obtained from

biomass should be renewable, nontoxic biodegradable and non-edible (Bringezu, 2009). Depends upon the current and future availability of feedstock, biofuel is classified into 1st, 2nd, and 3rd generation biofuel (Popp et al., 2014). The advantages of biofuel are it is a renewable energy source, biodegradable, low operating cost and reduces toxic emissions (Chisti, 2007; Hu et al., 2008). But the main disadvantage of biofuel is its limited availability, production of biofuel from edible sources causes food scarcity and also its production involves usage of land that ultimately decreases land availability for food production (Satyanarayana et al., 2011; Dismukes et al., 2008; Dorado et al., 2003).

Biofuel derived from Algae is considered as a third-generation biofuel hold several key advantages over the earlier feed stocks (Rinaldini et al., 2014). Algae are considered as potential feedstock and have high growth rate (30 to 100 times) while compared with conventional agricultural crops (Yang et al., 2016). Algae is a diverse group of aquatic organisms that have the ability to conduct photosynthesis. They are typically autotrophic, deriving their food or energy from their surroundings in the form of sunlight (Singh and Singh, 2015). The various properties like high oil content, fast growth, easy cultivation, short life span and high feasibility for diesel replacement are considered algae as a potential fuel source (Gallagher, 2011). Algae have a great

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tendency to grow on wetlands and this will lead to increase in production of biomass (Miranda et al., 2016). Microalgae have a high potential to get high yield with respect to low input are used widely for renewable energy application (Eboibi, 2019). Microalgae bio-oil in Transesterification improved its physicochemical properties with reduced engine emission (John et al., 2018). The combustion characteristic of engine is improved with respect to algae biofuel (Xu et al., 2016).

In the past few decades most research was carried out in the method of extracting biomass from algae. Reddy et al. (2014) investigated the extraction of fatty acid methyl ester from wet algae under supercritical conditions. The results reveals that 67% of fatty acid methyl ester for 20 min reaction time at 265 °C was obtained and 1:9 dry algae to ethanol (wt./vol.) ratio. In another work feedstock extracted from *Spirulina platensis* algae biomass using transesterification process was carried out. They found the optimum conditions for maximum yield of biodiesel about 75% were 90 min reaction time, 55 °C reaction temperature, 1:4 algae biomass ratio at 450 rpm string intensity (Nautiyal et al., 2014). In another work author extracted algae oil from *Isochrysis galbana* micro algae biospecies and they evaluated the physical and chemical properties of the oil. They estimated most suitable condition to estimate maximum yield are 30 min reaction time at 65 °C reaction temperature with NaOH as catalyst, 12: 1 methanol to oil molar mass (Silitonga et al., 2017). Similarly, another study involves the extraction of oil from algae source *Chlorella* alga by trans esterification process was studied. Process was carried out at 60 to 100 °C using sulfuric acid as a catalyst, it reveals that yield of around 98% at 20% wt sulfuric acid with 4 h reaction time was obtained (Viêgas et al., 2015). Dahlia M et al. (2015) investigated extraction of oil from marine macro-algae *Jania rubens* (Rhodophyceae), *Ulva linza* (Chlorophyceae) and *Padina pavonica* (Phaeophyceae) during the spring, summer and autumn. Results obtained reveals that *P. pavonica* shows higher fatty acid percentage 6.2% in autumn and *J. rubens*, with 68.6% in summer (El Maghraby and Fakhry, 2015). Panayiotis Tsaousis et al. (2014) conducted a theoretical simulation on diesel RK software by comparing raw algae and croton oil. Results obtained shows that algae oil produced lesser power with lower NOx emissions. On the other hand, it leads to more Brake Specific Consumption and increased CO₂ and PM emissions while compared with croton oil. The above mentioned works clearly indicated that bio oil extracted from algae is suitable replacement for diesel fuel.

In this work an attempt was made to extract biodiesel from bio source namely *Azolla Pinnata* algae species. *Azolla* is a Microalgal genus of seven species of aquatic ferns in the family salviniaaceae. They are found usually in Asian continents in rice fields, ponds, and ditches. It is also considered as one of rapid growing species and it almost doubles its yield for every 5 to 6 days (Arora and Singh, 2003). This alga has greater potential to grow on waste water and its unique chemical composition leads to consideration as universal feed stock for biodiesel production. Miranda et al. (2016) estimated the fatty acid methyl ester after transesterification of *Azolla* and it contains C16:0, C18:2 and C18. They stated *Azolla pinnata* found to be suitable replacement of diesel it matches various fuel properties like cetane number, Fuel density and iodine value (Yang et al., 2016). Present work solvent extraction technique is utilized to extract oil from *Azolla*, since it has higher oil percentage recovery rate. This method leaves only 0.5% to 0.7% residual oil content in the source after extraction (Topare et al., 2011). Micro algae obtained from *Azolla pinnata* is converted into Microalgae oil methyl ester using transesterification process. The various physical and chemical properties were tested and compared with ASTM standards. Further Experimental studies were carried out to evaluate its performance, Combustion and emission characteristics of the obtained fuel.



Fig. 1. Extraction of algae setup.

2. Materials and methods

2.1. Extraction of algal oil from *azolla pinnata*

Azolla pinnata was obtained and cultivated in a pit of size 9ft × 6ft × 1ft deep at Tamilnadu agricultural university, Coimbatore, India. *Azolla pinnata* as raw living biomass was taken to the laboratory immediately after collecting in a polythene bags. At first, the cultures were washed with water twice to remove epiphytes and sand particles. The rinsed algae were dried in a Hot Air Oven for 24 hrs at 50 °C. After the process of drying, the algae were pulverized, worked into powdered fine particles.

In order to extract algae biomass content soxhlet extraction is carried out using ethanol as solvent at 70 °C. In this technique 20 g of obtained algae powder is filled in the top layer of thimble. In Soxhlet extraction technique, the thimble was filled with 20 g of processed algae powder. Meanwhile in the 200 ml of ethanol is filled in the bottom layer of the extractor. Then the setup is heated up at 70 °C, while heating ethanol is vaporized and reacts with algae biomass at the top layer. Algae biomass mixes with chloroform–methanol lead to the formation of colloidal solution. This solution is collected in the round-bottomed flask, this entire process completes one cycle in 8 to 10 mins. Similarly, the cycle is repeated for 22 to 26 times and lipid from algae biomass is collected in the bottom flask as shown in Fig. 1.

2.2. Production of biodiesel

Biodiesel obtained usually has high viscosity and density because of the presence of high fatty acids in its molecular structure. This fatty acid can be converted into monoalkyl esters by reacting one mole of triglyceride with alcohol (methanol or ethanol). It involves the obtained lipids is converted into ester by reacting with methanol in the presence of acid catalyst. Conversion efficiency depends upon molar ratio of alcohol to oil and will determine biodiesel yield and production. In this present work methanol to oil ratio of 6:1 and 10 ml of H₂SO₄ is made to react at 60 °C for 45 min. in a magnetic stirrer. After complete conversion, the extract was let to separate overnight in a separating funnel. The extract was separated into three layers. In which the layer in the bottom of the separating funnel is impurities and glycerin. The top layer



Fig. 2. Transesterification process.

Table 1
FTIR analysis result.

S.No	Value	Range	Bond structure	Functional group
1	3377.36	3400–3300	N–H	Aliphatic primary amine
2	2945.3	3000–2840	C–H	Alkane
3	2835.36	2840–2695	C–H	Aldehyde (Doublet)
4	1672.28	2000–1650	C–H	Aromatic compound
5	1456.26	1465–1450	C–H	Alkane (Methylene)
6	1413.82	1395–1440	O–H	Carboxylic acid
7	1213.23	1215–1163	C–O	Ester
8	1112.93	1150–1085	C–O	Aliphatic ether
9	1018.41	1070–1010	C–O	Vinyl ether
10	763.81	665–840	C=O	Alkene
11	657.73	690–515	C–Br	Halo compound
12	599.86	600–500	C–I	Halo compound

is pure biodiesel. The layer in between the top and bottom layers are in viscid so they have to be separated. Fig. 2 shows the process of Transesterification of algae oil. The maximum yield of around 8.25 g is obtained after this process.

2.3. FTIR spectroscopy

FTIR-Spectroscopy testing was carried out in South Indian Textile Research Association, Coimbatore. In this analysis, Nicolet IS 10 model machine, Thermo Scientific make was used to carry out FTIR analysis. The machine spectrum was recorded between 3995.85 and 455.13 cm^{-1} . Table 1 shows the FTIR analysis results. The analysis and presence of various functional groups were carried out in FTIR and the range values are given in the Table 1. By evaluating the functional groups and its vibrations, quality and important fatty acid methyl ester of biodiesel could be foretold. In FTIR analysis, Samples as small as 10 μm can be evaluated effectively. The smaller size sample allows effective identification of particles, residues, films or fibers. The levels of oxidation or degrees of cure in some polymers as well as measuring the level of contaminants or additives can be measured in FTIR analysis (Hariram et al., 2019) (see Fig. 3).

2.4. GC-MS analysis

The gas-chromatography analysis was used to analyze the complete transesterification of Triglycerides into Fatty Acid Methyl

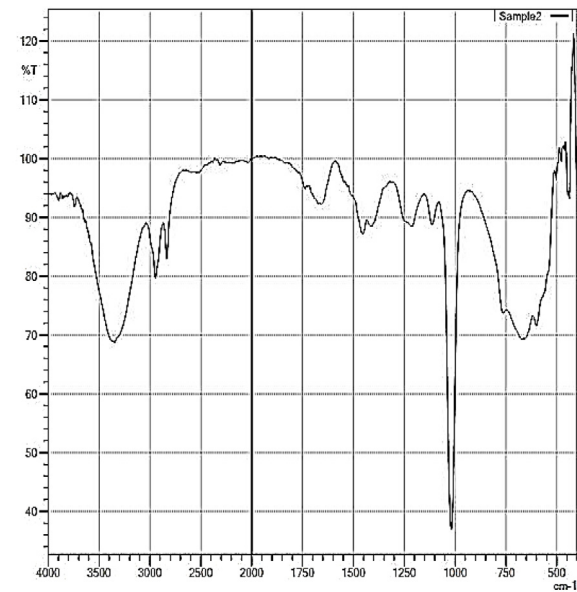


Fig. 3. FTIR analysis result of Algae biodiesel.

Table 2
Components identified using GC-MS.

Peak No.	Peak ID	Ret time	Height	Area%	Concentration
1	n_heptane	3.1480	541248.5630	776941.3130	99.4537
2	Palmitic	13.1900	182.6130	617.1500	0.0790
3	Stearic	16.4980	209.5560	734.6500	0.0940
4	Oleic	17.1650	396.1250	1380.0000	0.1766
5	Linoleic	18.2570	400.9470	1393.9000	0.1784
6	Linolenic	19.5570	38.6000	142.2000	0.0182
Total			542476.4030	781209.2130	100.0000

Ester. In this work, Thermo-GC-MS Trace Ultra equipment, version 5.0 was used to perform GC-MS analysis and it is coupled with data acquisition system version 2.0. The Fatty Acid Methyl Esters presence indicates the feasibility of using the biodiesel as an alternative to fossil fuel. In this investigation, algal biodiesel of 1ml was passed through column of Perkin Elmer gas chromatograph-mass spectrometer and nitrogen was used as carrier gas of flow rate 1.0 ml/minute. Peaks obtained for sample was identified by comparing with n-Hexane standard of the biodiesel. The chemical composition in algae oil was given in Table 2. The obtained values of mass spectra were analyzed and matched with the available references in NIST and WILESY mass spectra library (Sakthivel and Ramesh, 2017). From the results of GC-MS analysis, the presence of linoleic in algae fuel makes it reasonable alternative for diesel fuel. Table 3 shows the Physical and chemical properties of diesel and Algae biodiesel blend. Table 4 shows the apparatus details for diesel and Algae biodiesel properties measurement (see Fig. 4).

In this work flash and fire point of the fuels were found by using Abels flash and fire point Apparatus. This apparatus will determine the flash and fire point of any petroleum fuel with the accuracy of about ± 2 $^{\circ}\text{C}$ and it is tested as per ASTM D92 standards. Cloud and Pour point were determined as per ASTM 2500 standards which can measure up to -55 $^{\circ}\text{C}$. Viscosity of the fuels and its blends were found by using redwood viscometer as per ASTM D 1298 standards and have accuracy of about ± 3 $^{\circ}\text{C}$. The calorific value was found using Boys gas calorimeter as per ASTM D240 standards.

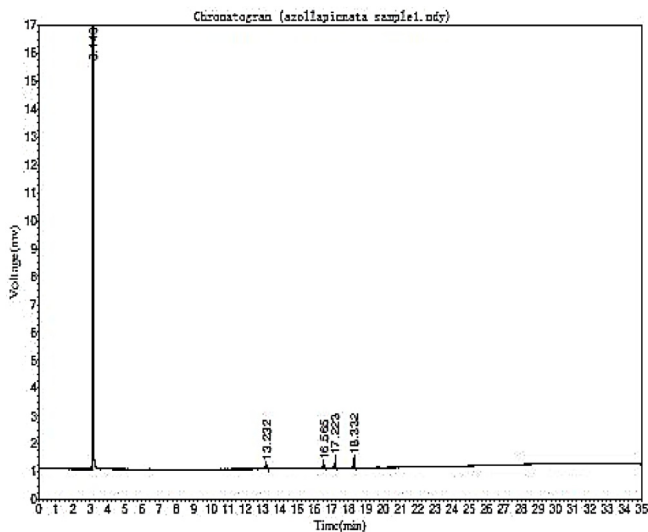


Fig. 4. GC-MS Chromatogram of Algae biodiesel.

Table 3
Physical and chemical properties of diesel and algae biodiesel blends.

S. No	Properties	Unit	Method	Diesel	Biodiesel (A100)	A20
1	Flash point	°C	ASTM D92	52	46	49
2	Fire point	°C	ASTM D92	78	61	71
3	Cloud point	°C	ASTM 2500	-5	6	-3
4	Pour point	°C	ASTM 2500	-4	3	-1
5	Viscosity	mm ² /s	ASTM D88	3.57	5.58	4.27
6	Density	kg/m ³	ASTM D1298	822	880	803
7	Calorific value	kJ/kg	ASTM D240	43 231	30 881	39 678

3. Experimental setup and testing

3.1. Experimental setup

In this work the experiments were carried out in a single-cylinder, four-stroke, naturally aspirated, water-cooled, CRDI engine. The layout of the experimental setup is shown in Fig. 5. Eddy current dynamometer was used to load the engine. Piezoelectric pressure transducer in the cylinder head and crank angle sensor are employed to obtain combustion parameters. A high-speed data acquisition is used to get a pressure vs crank angle data and displayed in a computer. Then a corresponding size analysis was done by using particle size analyzer. Exhaust gas temperature at various locations of tailpipe was found using J type thermocouple. HC and NO_x emission was measured using AVL Digas Analyser. Smoke intensity was measured by using AVL smoke meter.

Table 4
Apparatus details for diesel and algae biodiesel properties measurement.

Parameter	Name of the apparatus	Make	Specifications of equipment	Accuracy
Flash and fire point	Abels flash and fire point Apparatus	HAMCO	This apparatus is suitable for determining the close cup flash point of petroleum and mixtures According to IP 33 and IP 170 and also IS 1448 (Part 1) 1985 (P:20). It is suitable for oils Whose flashes below 70 deg C. It is supplied with oil cup, cover fitted with stirrer, thermometer Socket S.S. Water Bath, Stand. An electric heater is fitted at bottom for Operation on 220 V AC Circuits. With oil test jet, electric heating with energy regulator control.	
Cloud & pour point	Cloud and pour point apparatus	HAMCO	Refrigerated unit SINGLE Compartment as per IP-15 & 219 & ASTM D 2500,IS 1448(P-10) -55 °C with control panel.	
Red wood viscometer	Red wood viscometer	HAMCO	As per IP 70 with Stainless Steel Jet (Viscosity above 2000 s) electrically heated model with energy regulator (Digital model)	Accuracy : +/- 3 °C 7) Readability : +/- 0.5 °C
Boys gas calorimeter	Boys gas calorimeter	VENUS	Boys gas calorimeter to determine the calorific value of gas (By digital weighing balance with 2 kg LPG Cylinder)	

Table 5
Engine specifications.

S.NO	Parameter	Details
1	Make	Kirloskar engines
2	No. of cylinder	1
3	Bore	80 mm
4	Stroke length	110 mm
5	Speed	1500 rpm
6	Maximum power	5 hp (3.7 kW)
7	Swept volume	780 cm ³
8	Compression ratio	16.5:1
9	Lubricating oil	SAE30/ SAE40
10	Type of lubrication	Splash type
11	Cooling system	Water
12	Injection timing	27° BTDC
13	Injection pressure	200 bar

3.2. Experimental procedure

Fig. 6 shows the test engine used in the experiment. Initially, the engine was allowed to warm up for 10 to 15 min at idle load conditions until it reaches its steady state condition. Then the water supply to the engine was checked to ensure proper cooling of the engine. The lubricating oil level was checked and calibrations were made on the dynamometer to avoid loading error. Once the engine attains steady-state condition exhaust emission measuring instruments were connected in the tailpipe. Before connecting those devices calibration was done in order to avoid any interference in test results. Then the engine was meant to run at various load conditions (0%, 25%, 50%, 75%, and 100%) and the results are obtained. Table 5 shows the specifications of the engine.

4. Uncertainty evaluation

The accidental errors happen during the measurement of reading during experimental test. A logical error often happens due to the poor calibration of measuring equipment. The designing and manufacturing of equipment varies which produces error in the equipment.

It is necessary to evaluate uncertainty in any experimental testing. Uncertainty evaluation is carried out by repeating any experiments for 4 to 5 times and taking the standard deviation to the measured values uncertainty values are evaluated. The uncertainty of any experimental measurement is calculated based on Kline and Mc.Clintock method (Kline, 1953; Holman et al., 2001). Table 6 shows the percentage of uncertainty of the measured parameters. The formulae used in evaluating the uncertainty are the following.

$$\Delta R = \left[\left(\frac{\partial R}{\partial x_1} \Delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \Delta x_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \Delta x_n \right)^2 \right]^{1/2}$$

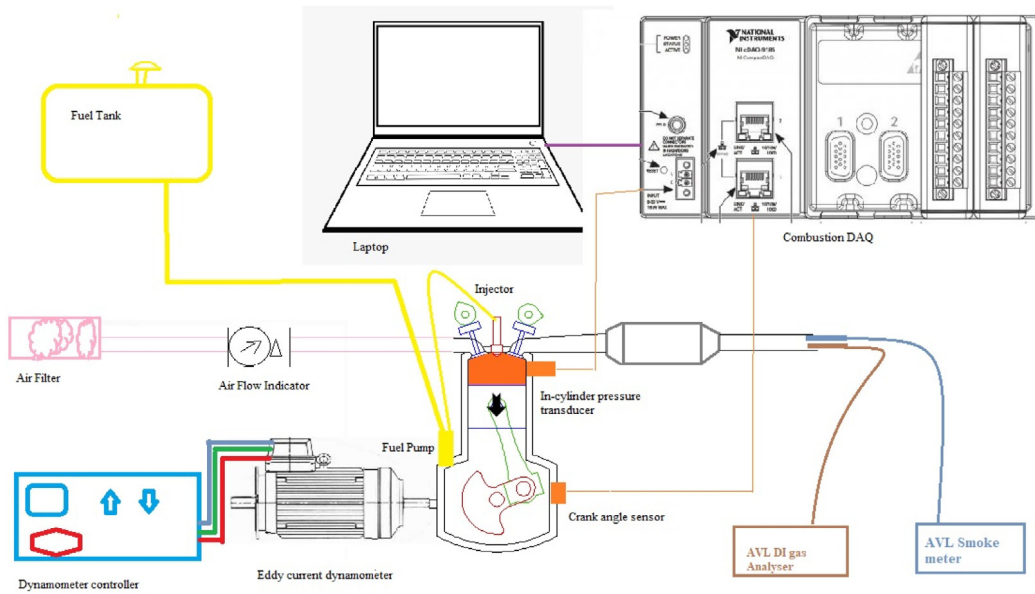


Fig. 5. Layout of the experimental setup.

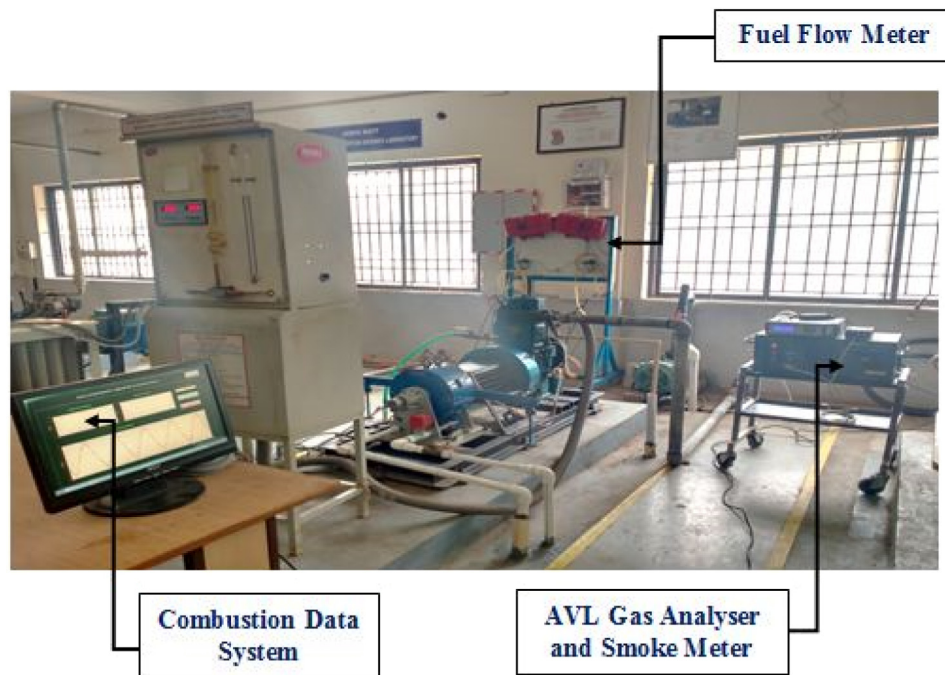


Fig. 6. Experimental test engine.

ΔR is the total uncertainty of the experimental result.

R-Given function and depends on independent variables like X_1, X_2, \dots, X_n .

$\Delta x_1, \Delta x_2 \dots \Delta x_n$ - Independent variable uncertainties.

Based on the analysis, total uncertainty was determined within the limit of $\pm 3.25\%$

5. Results and discussion

5.1. Specific fuel consumption

The term SFC implies the amount of fuel consumed per unit brake power. It indicates the efficiency of the work obtained from the given fuel. Fig. 7 shows the comparison between Brake Power

Table 6
Percentage of uncertainty.

S.NO	Parameter	Uncertainty (%)
1	Brake thermal efficiency	0.7
2	Brake specific fuel consumption	0.8
3	Total fuel consumption	0.7
4	Brake power	0.5
5	Pressure	0.7
6	Speed	1.1
7	Oxides of nitrogen	0.8
8	Carbon monoxide	0.7
9	Hydrocarbon	0.5
10	Smoke	0.6

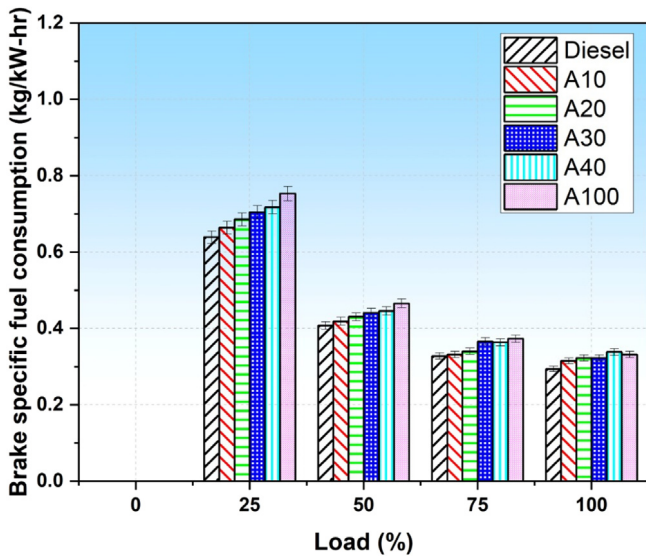


Fig. 7. Variation of specific fuel consumption against engine load.

and SFC. The trend obtained shows that as applied load increases SFC decreases for both algae blends and diesel. As the applied load increases the in-cylinder temperature rises this increases the fuel burning rate. Compare to algae blends diesel fuel consumed minimum fuel to produce power. The main reason is that diesel has more calorific value while comparing to algae. At lower load conditions algae and its blends consumes more fuel while compared with diesel. This trend occurs due to higher viscosity of algae as shown in Table 3 it consumes more fuel than neat diesel. However, at higher load conditions algae blends show similar SFC while compared with diesel. Maximum of around 7% variation in SFC is observed at no load and part load conditions. Since as load increases in cylinder temperature also rises this decreases the viscosity of algae blends thus improves the combustion which leads to lower SFC.

5.2. Total fuel consumption

The term TFC indicates the amount of fuel consumed to produce brake power on hourly basis. Fig. 8 shows the comparison between Brake power and TFC. The trend obtained reveals that TFC increases linearly with the applied load. This scenario occurs since as applied load increases amount of fuel injected increases this leads to more consumption of fuel. Compare to Algae blends diesel has lower TFC since biodiesel has calorific value than neat diesel. So it consumes more amount of fuel to produce similar brake power. Then also the algae and its blends a has higher viscosity, density and lower calorific value as shown in Table 3 leads to higher TFC. Among the blends A20 obtained similar trend with diesel and all other blends have maximum variation with 10%. This clearly points out that algae fuel is better replacement for neat diesel fuel.

5.3. Brake thermal efficiency

Brake thermal efficiency indicates the ratio of output power developed by the engine to the fuel supplied as input. Fig. 8 shows that brake thermal efficiency for diesel and algae blends. From the figure, it shows clearly that BTE of algae is slightly lower than neat diesel. The main reason behind this scenario is that Biodiesel has High viscosity, low volatility, and improper air–fuel mixing. This parameter leads to poor spray characteristics which will increases

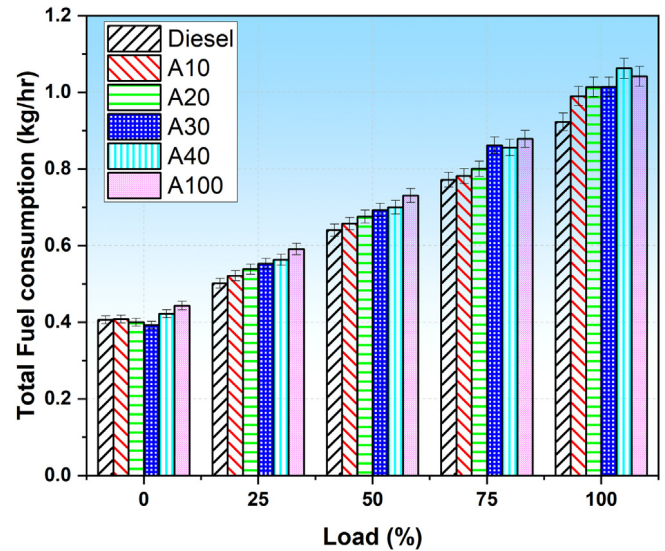


Fig. 8. Variation of total fuel consumption against engine load.

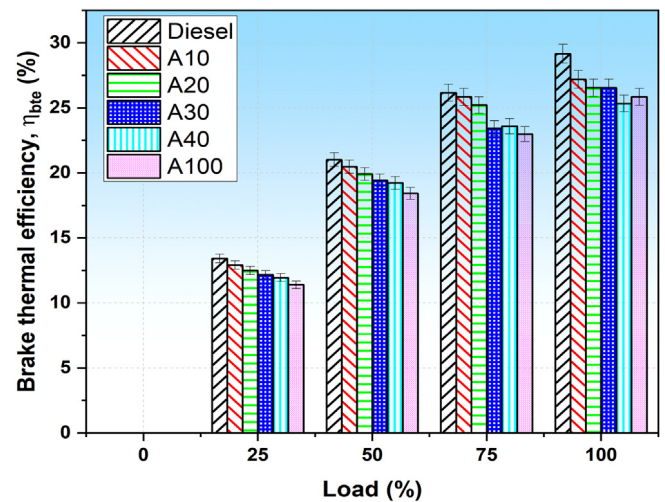


Fig. 9. Variation of brake thermal efficiency against engine load.

ignition delay and it leads to burning of fuel later in expansion stroke (Pattanaik and Misra, 2018).

The BTE increases with the increase in applied load for both diesel and algae blends. This scenario occurs since as applied load increases the quantity of fuel injected, this leads to a rise in-cylinder temperature. This factor reduces ignition delay and improves air–fuel mixing leads to complete burning of fuel. Among the biodiesel blend algae A20 shows higher BTE 25% and A100 have lower BTE of around 28% at higher load conditions. Pure algae oil has higher viscosity and density as mentioned earlier leads to poor atomization which reduces BTE (see Fig. 9).

5.4. Exhaust gas temperature

Fig. 10 shows the variation of exhaust gas temperature for diesel and biodiesel blends. The trends show that there is only slight variation in temperature is observed between diesel and algae blends. The maximum difference of around 20 °C is obtained between diesel and its algae blends. The reason for this coherency indicates that the combustion profile and heat loss profile obtained is similar for different fuels used (Datta and Mandal, 2012).

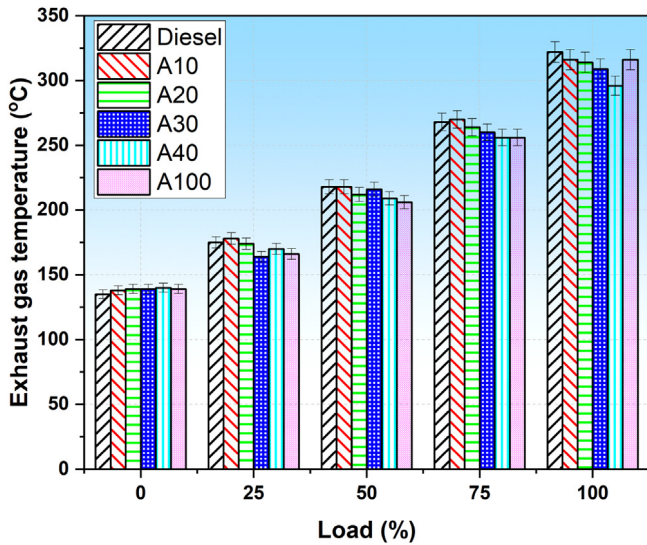


Fig. 10. Variation of exhaust gas temperature against engine load.

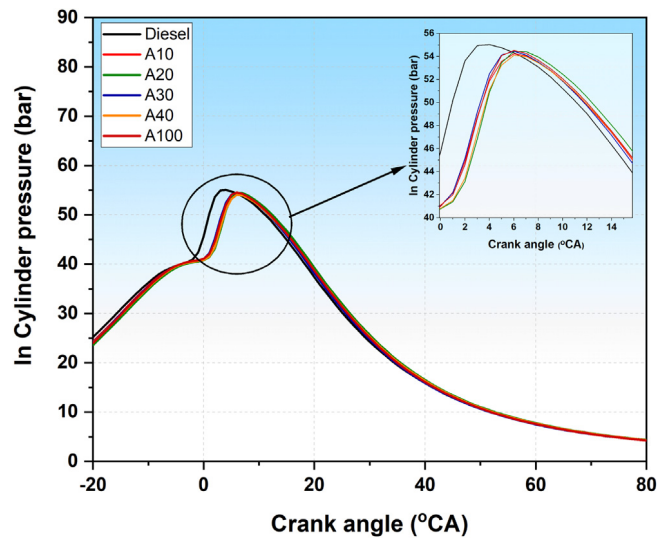


Fig. 11(b). Variation of in-cylinder pressure against 25% load.

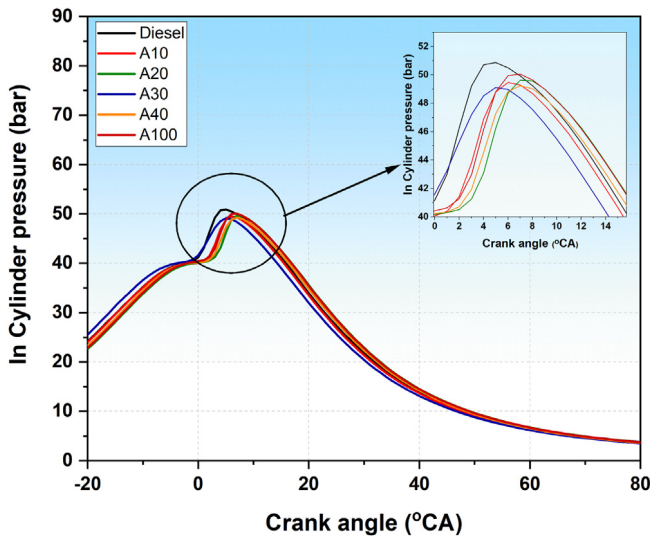


Fig. 11(a). Variation of in-cylinder pressure against 0% load.

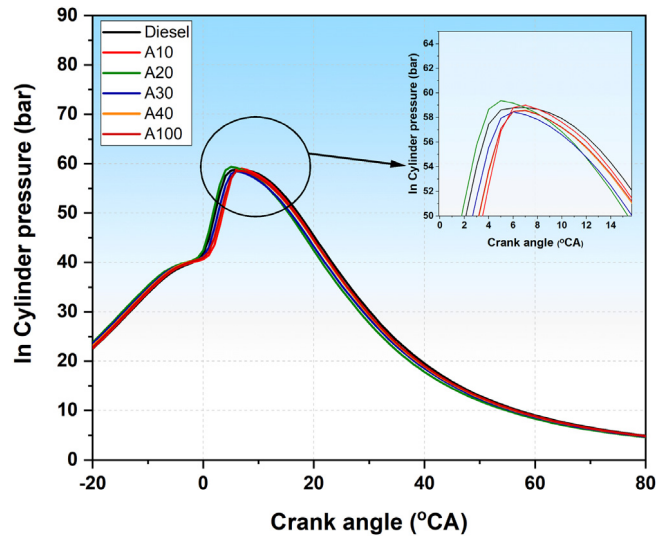


Fig. 11(c). Variation of in-cylinder pressure against 50% load.

5.5. Combustion characteristics

Figs. 11(a) to 11(e) shows in-cylinder pressure variation with crank angle of diesel and algae blends of biodiesel at various load conditions. It shows clearly that peak pressure increases as the applied load are increases. Which leads to increased amount of fuel injected. The fuel contains more amount of carbon particles, this ultimately increases calorific value of fuel so it leads to peak pressure rise. Peak pressure obtained almost similar between diesel and biodiesel for all loads. The peak pressure of diesel is only about 3 to 11% higher while compared with blended diesel. This main reason for this slight variation is that as already quoted biodiesel has higher viscosity and lower calorific value (Agarwal, 2007). The maximum peak pressure of around 67 bar is obtained for diesel at higher load condition. For A20 blend 63 bar is obtained at similar conditions this shows clearly algae blends have effective replacement for diesel fuel.

Fig. 12 shows the heat release rate for various blends of diesel and biodiesel. Heat release parameter mainly indicates the chemical energy available in the fuel. The trend obtained

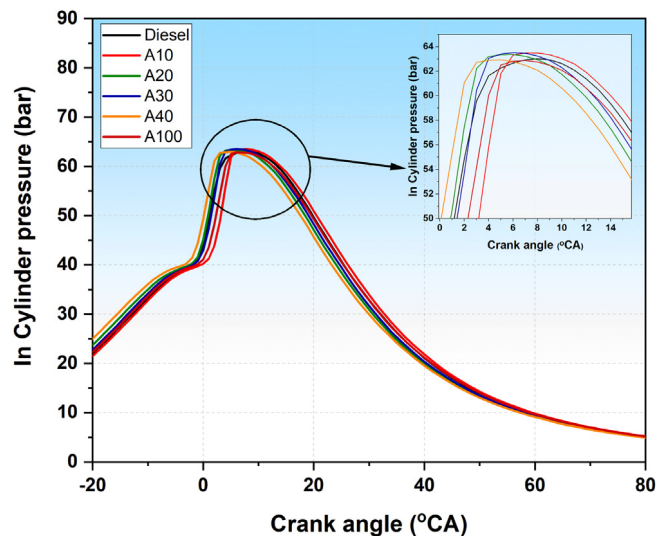


Fig. 11(d). Variation of in-cylinder pressure against 75% load.

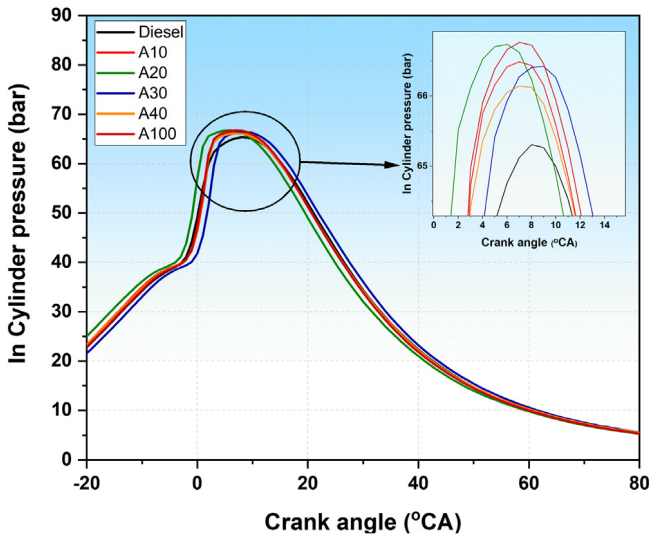


Fig. 11(e). Variation of in-cylinder pressure against 100% load.

clearly indicates that HRR increases as applied load increases. This Scenario occurs since as applied load increased amount of fuel injected also rises so the fuel admitted contains more amount of carbon particles. More amount of fuel particles increases energy content of fuel thus increases HRR. Trend obtained also reveals that biodiesel blends shows higher or almost similar HRR while compared with diesel. This occurs since biodiesel has high viscosity and lesser calorific value while compared with diesel it increases the ignition delay of biodiesel and its blends. Increased

ignition delay prolongs the period of pre mixed combustion phase and decreases diffusion combustion phase while compared with pure diesel. Among the various blends tested A10 shows 10% rise in HRR at higher load conditions while compared with all other blends. The core reason is that as higher applied load conditions in cylinder temperature seem to be high this increases the oxidation reactions. Another reason is that the viscosity also reduces at higher temperature this decreases ignition delay of biodiesel further. Final conclusion says that algae and its blends shows maximum variation of around 15% HRR at all applied load conditions while compared with diesel. Algae blends have greater potential to replace the diesel fuel and reduces the fossil fuel depletion.

5.6. Unburned hydrocarbon

Fig. 13 shows the variation of hydrocarbon emission for diesel and Algae blends. The trend obtained indicates clearly that HC linearly decreases for biodiesel blends. The reduction percentage of around 50% is observed for all algae blends at no load and full load conditions. A30 blends show a higher percentage reduction of around 62% at higher load conditions. This scenario occurred since biodiesel has a higher cetane number while compared with diesel improves the ignition quality of fuel and promotes complete oxidation (Ghudasara and Ghudasara, 2012; Mohankumar and Senthilkumar, 2017). Another reason is that since biodiesel has higher viscosity it has longer ignition delay it further leads to prolonged diffusion combustion duration leads to complete burning of fuel. Another core reason is that algae fuel contains oxygen content in its fuel structure naturally this further enhances oxidation leads to complete burning of fuel (Tsaousis et al., 2014; Arora and Singh, 2003). This factor finally results in better combustion lower HC emission.

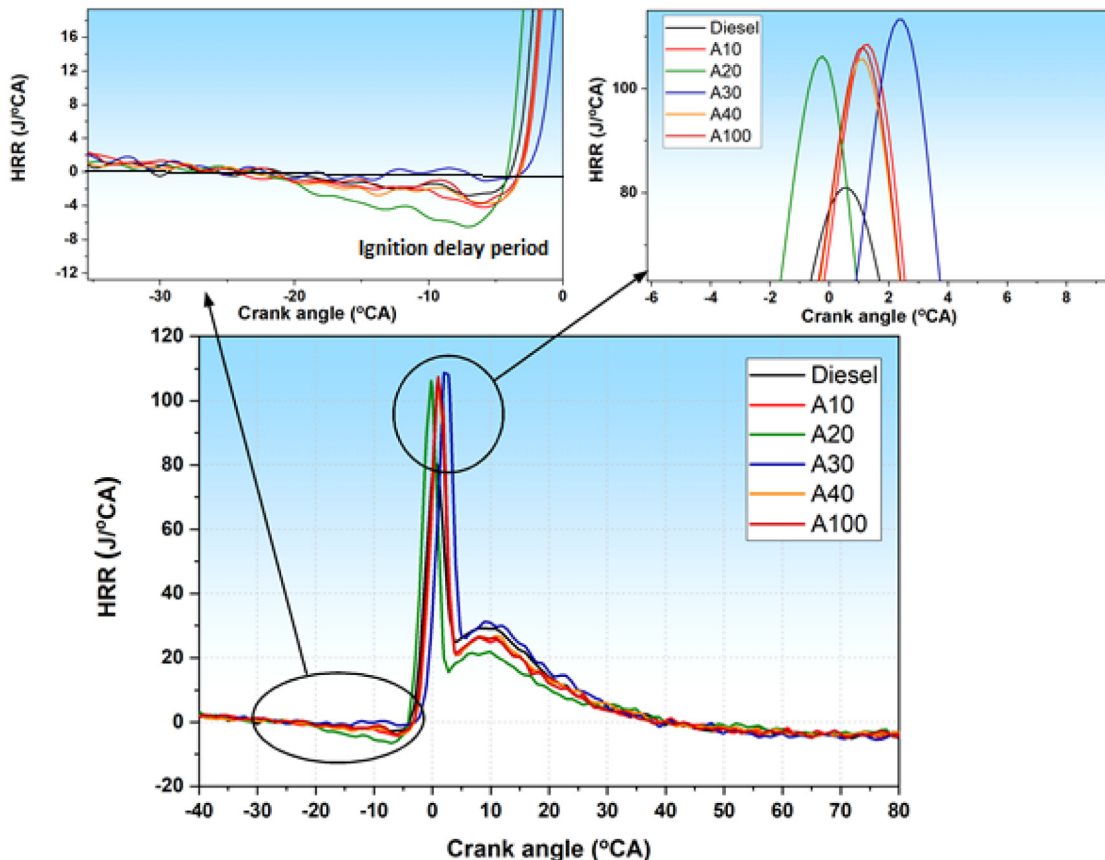


Fig. 12. Variation of heat release rate at engine full load condition.

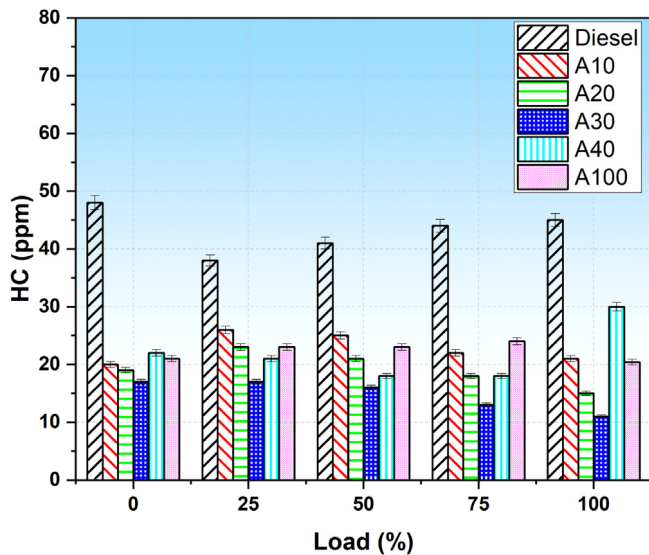


Fig. 13. Variation of hydrocarbon against engine load.

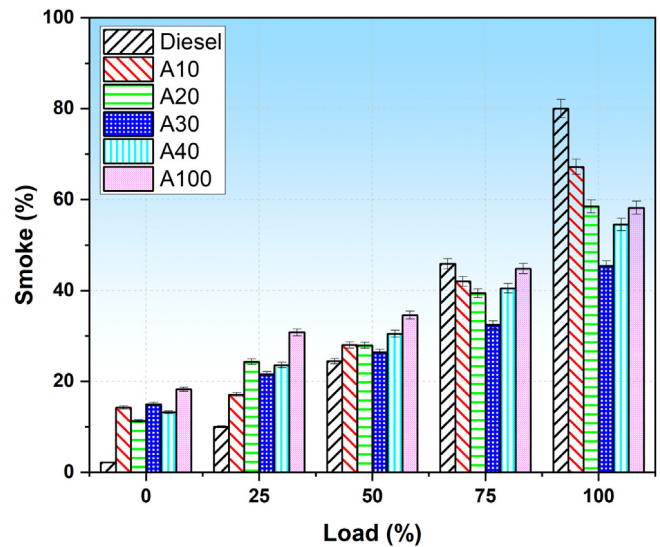


Fig. 15. Variation of smoke against engine load.

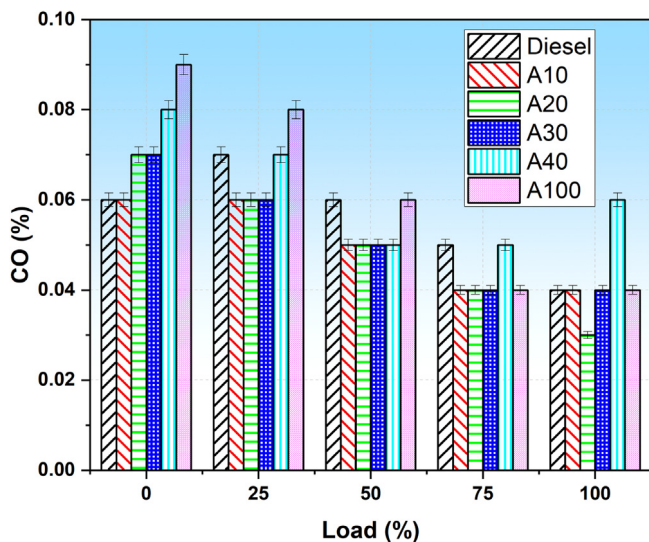


Fig. 14. Variation of carbon monoxide against engine load.

5.7. CO emission

Fig. 14 shows the variation of CO emission for different fuels used. The Trend obtained pointed out that CO emission is high at lower loads and it reduces at higher loads. At Low load A100, A40 shows almost 30% and 25% rise in CO emissions. The main reason is that CO emission formed due to low in-cylinder temperature, and rich air-fuel mixture formed inside the cylinder. At lower loads due to low in-cylinder temperature, over lean mixture and poor atomization of biodiesel, higher viscosity and density of algae blends leads to higher CO emissions (Mani et al., 2009; Ramadhas et al., 2005). At higher load conditions molecular oxygen concentration improves and the cylinder temperature also rises which will promote oxidation and reduces viscosity this factors leads to reduction of CO emissions for both diesel and algae blends (Tan et al., 2012).

5.8. Smoke opacity

Smoke opacity formation occurs due to formation of rich mixture during combustion at high temperature and pressure. Due to

Heterogeneous nature of diesel engine, the air-fuel mixture composition varies greatly across the combustion chamber. Fig. 15 shows the variation of smoke emission at various load conditions. The obtained trend shows that smoke emission decreased gradually for algae and its blends. Maximum of around 30% reduction for A100 and other blends shows considerable reduction while compared with neat diesel. As discussed earlier algae fuel is partially oxygenated, this factor enhances oxidation reactions. Then also algae have less calorific value than diesel this reduces combustion temperature and pressure further leads to reduction of smoke emissions (Pal et al., 2010).

5.9. NOx emission

Fig. 16 shows the variation of NOx emission for algae blends and diesel. The graph reveals that NOx emission linearly increases with the applied load for both the fuels. NOx formation mainly depends on combustion temperature and oxygen concentration available in combustion product (Subramaniam et al., 2016; Muthiya and Pachamuthu, 2018; Solomon et al., 2019). Generally NOx increases linearly with the load since as load increases, fuel to air ratio also rises this finally increase the average gas temperature (Parthiban et al., 2017). The heat release is high for all algae biodiesel blends, but NOx reduction is observed for all algae biodiesel blends. NOx emission is reduced mainly due to the low combustion duration and less time available for conversion of nitrogen to NOx. This phenomenon reduces average gas temperature leads to reduction of NOx emissions. It is observed that for all biodiesel blends NOx emissions reduce significantly from no load to full load. A100 shows maximum reduction of around 39% while compared with diesel and other blends. The main reason is that biodiesel has poor spray characteristics due to its higher viscosity and density as shown in Table 3. And it will leads to improper combustion.

6. Conclusion

In this present investigation biodiesel extracted from *Azolla pinnata* algae is tested in single cylinder direct injection diesel engine. In Initial part of this study, Physical and chemical characteristics of diesel and algae blends were analyzed. Then experimental studies are carried out by running the engine at various load

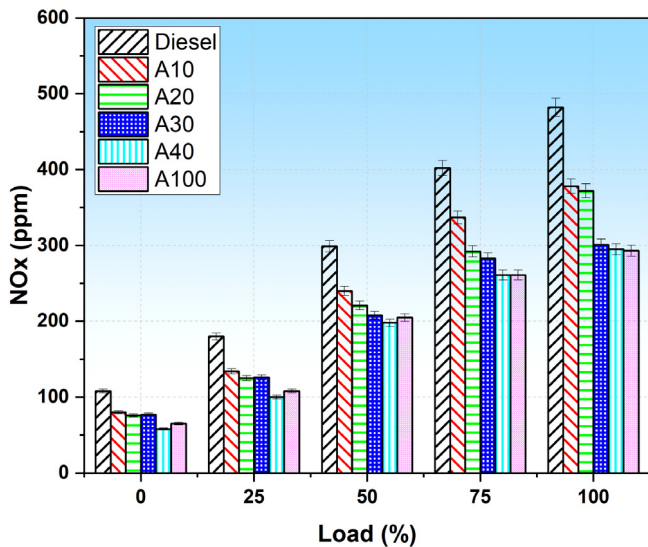


Fig. 16. Variation of oxides of nitrogen against engine load.

conditions and the corresponding performance, Combustion and emission characteristics were studied. The various conclusions made from the present study are as follows

- Applied load increases SFC decreases for both algae blends and diesel. However, at higher load conditions algae blends show similar SFC while compared with diesel. Maximum of around 7% variation in SFC is observed at no load and part load conditions.
- TFC increases linearly with the applied load for both diesel and biodiesel. Among the blends, A20 obtained similar trend with diesel and all other blends have maximum variation with 10%.
- Regarding BTE Blends of algae shows slightly lower than Algae blends. Among the biodiesel blend algae A20 shows higher BTE 25% and A100 have lower BTE of around 28% at higher load conditions
- For Exhaust temperature there is only slight variation in temperature is observed between diesel and algae blends. The maximum difference of around 20 °C is obtained between diesel and its algae blends.
- Regarding combustion characteristics, the peak pressure of diesel is only about 3 to 11% higher while compared with blended diesel. HRR for algae and its blends shows maximum variation of about 15% while compared with diesel fuel.
- Regarding HC emission the reduction percentage of around 50% is observed for all algae blends at no load and full load conditions. A30 blends show a higher percentage reduction of around 62% at higher load conditions.
- CO emission is high at lower loads and it reduces at higher loads. At Low load A100, A40 shows almost 30% and 25% rise in CO emissions.
- Regarding smoke emissions Maximum of around 30% reduction for A100 and other blends shows considerable reduction while compared with neat diesel
- NOx emission linearly increases with the applied load for both the fuels. However, for algae blends, it reduces significantly from no load to full load. A100 shows maximum reduction of around 39% while compared with diesel and other blends

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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