

# Evaluation of performance and emission characteristics of heterotrophic chlorella protothecoides microalgae biodiesel and its blends with diesel in a direct injection diesel engine.

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**Abstract.** At present research in biofuels for internal combustion engines received a lot of attention because the fossil fuels are depleting in nature and also due to their exhaust emissions they imposing threats like global warming, acid rain etc on environment. The use of biofuels derived from plant biomass in internal combustion engines can reduce the global warming and other hazards on environment, but the difficulty associated with these fuels is the feed stocks, fertile land requirement for their growth resulting in shortage of fertile land for cultivating food crops. So algae are the best alternative promising biofuel resource energy. Particularly microalgae are most reliable source of biofuel because they are non edible, and they does not require fertile land for their growth. Hence, Accordingly, in this research work Heterotrophic chlorella prothecoides microalgae biodiesel, diesel and their blends are tested with a DI diesel engine to study the performance and emission characteristics. The experimental study shown that, compared to Petroleum diesel the Heterotrophic chlorella protothecoides microalgae biodiesel produces lesser emissions. Heterotrophic chlorella protothecoides microalgae biodiesel B100 shown a reduction of 2.85, 2.89, 3.15, 20, 4.67 and 13.54 % in, torque, brake power, brake thermal efficiency, CO, CO<sub>2</sub> and NO<sub>x</sub>, respectively and an increase of 11.81 and 15.96 % in O<sub>2</sub> and bsfc, respectively compared to petroleum diesel.

## 1. Introduction

The energy demand is growing worldwide. Fossil fuels fulfilled about 80% of this energy with the green house gas emissions and also in future the fossil fuel reserves will exhaust. BP Statistical Review of World Energy 2019 reveals the following data represented in tables 1.a, 1.b and 1.c, which indicates a gap between oil consumption and supply is about 4287 thousand barrels daily in India [1]. So this motivates for research for biofuels to meet the energy demand with lesser emissions.



**Table 1. a** Proved oil reserves

<b>At end 2018</b>				
	Thousand million tonnes	Thousand million barrels	Share of total	R/P ratio
India	0.6	4.5	0.3%	14.1
World	244.1	1729.7	100%	50.0

**Table 1. b** Oil production

	<b>Thousand barrels daily 2018</b>	<b>Change 2018 over 2017</b>	<b>2018 share of total</b>
India	869	-1.7%	0.9 %
world	94718	2.4%	100.0 %

**Table 1. c** Oil consumption

Thousand barrels daily	2018	Change 2018 over 2017	2018 share of total
India	5156	5.9 %	5.2 %
world	99843	1.5%	100.0%

The fossil fuel resources are not considered as reliable sources in near future because they are depleting in nature and are questionable from the ecology, environmental and economic point of views. The emissions of NO<sub>x</sub>, hydrocarbons, smoke, SO<sub>x</sub>, particulate matter, carbon are less with combustion of biofuels compared to fossil fuels. Because of the many advantages of biofuels over the fossil fuels, the production of biodiesel has attracted much attention in recent years.

At present India is the one of the largest and the fastest growing energy consumers in the world due to raising population and power consumption in India. Pollution from the vehicles contributes approximately about 70% to the total air pollution and is estimated to have increased about 7-8 times in the last two decades. Due to limited crude oil reserves, India meets about 72% of its crude oil and petroleum products requirements through imports, which are expected to expand further in coming years. Biofuel is to be an appropriate option to be fixed as a solution to these problems.

## 2. Materials and methods.

### 2.1 Biofuel material selection and collection

The lipid content of the microalgae biofuel is considered as one of the most significant aspects to select proper algal strains for biofuel production. Microalgae contains oil levels between 20 to 80 % by dry weight. [2] and [3]. The species selected for this study is the green microalgae *Chlorella* that may be grown both autotrophically and heterotrophically. Green microalgae *Chlorella* is one of the identified species in research field compared with other various algae strains. Heterotrophic *Chlorella*

protothecoides microalgae biodiesel is selected for the present work because it contains the crude lipid content of 55.2%. [4].

**Table 2** Physiochemical properties of heterotrophic chlorella protothecoides microalgae biodiesel [5]

Properties	Biodiesel from Heterotrophic Chlorella Protothecoides Microalgae biodiesel	Diesel fuel	ASTM biodiesel standard
Density ( $\text{kg}\cdot\text{L}^{-1}$ ) at $15^{\circ}\text{C}$	0.864	0.838	0.84 – 0.90
Viscosity ( $\text{mm}^2\cdot\text{s}^{-1}$ , cP at $40^{\circ}\text{C}$ )	4.44	1.9 – 4.1	3.5 – 5.0
Flash Point ( $^{\circ}\text{C}$ )	115	60	Min 100
Solidifying point ( $^{\circ}\text{C}$ )	-12	-50 to 10	-
Acid value ( $\text{mg KOH}\cdot\text{g}^{-1}$ )	0.373	Max 0.5	Max 0.5
Heating value ( $\text{MJ}\cdot\text{kg}^{-1}$ )	39.11	40 – 45	-

Heterotrophic chlorella protothecoides microalgae oil was collected from Soley Institute Turkey. Almost all the common FAMES content are present in the Heterotrophic chlorella protothecoides microalgae biodiesel. The most common fatty acids of microalgae are Palmitic-(hexadecanoic-C16:0), Stearic-(octadecanoic-C18:0), Oleic(octadecenoic-C18:1), Linoleic (octadecadienoic -C18:2) and Linolenic-(octadecatrienoic-C18:3) acids [6]. Higher oleic acid content decreases the cold filter plugging point (CPPF) for the use in cold regions [7] and increases oxidative stability for longer storage [8].

## 2.2 Experimental set-up and methodology



**Figure 1.** Photo of IC Engine test rig.

Figure 1. shows the experimental setup. The investigation was conducted on a computerized single cylinder, 4 stroke, water cooled, stationary Kirloskar DI diesel engine with a combustion analysis

software called 'IC Engine soft' to measure engine performance and exhaust gas emissions. And its rated power is 5.2 kW/7 hp @ 1500rpm. Two separate fuel tanks with a fuel switching system are used, one for diesel (D100) and the other for biodiesel (B100). A Engine is coupled with an eddy current dynamometer to control engine torque through computer. A piezoelectric pressure transducer is installed in engine cylinder head to measure combustion pressure.

**Table 3.** Engine details

Sl No	Parameters	Specification
1	Type	TV1 ( Kirloskar make)
2	Software used	Engine soft
3	Nozzle opening pressure	200 to 225 bar
4	Governor type	Mechanical centrifugal type
5	No. of cylinders	Single cylinder
6	No. of strokes	Four stroke
7	Fuel	H. S. Diesel
8	Rated power	5.2 kW (7 HP at 1500 RPM)
9	Cylinder diameter (Bore)	0.0875 m
10	Stroke length	0.11 m
11	Compression ratio	17.5 : 1
12	Air Measurement Manometer	
	a) Type	U- Type
	b) Range	100 – 0 – 100 mm
13	Eddy current dynamometer	
	a) Type	Eddy current
	b) Maximum	7.5 KW ( at 1500 to 3000 RPM)
	c) Flow	Water must flow through Dynamometer during the use
14	Fuel measuring unit – Range	0 to 50 ml

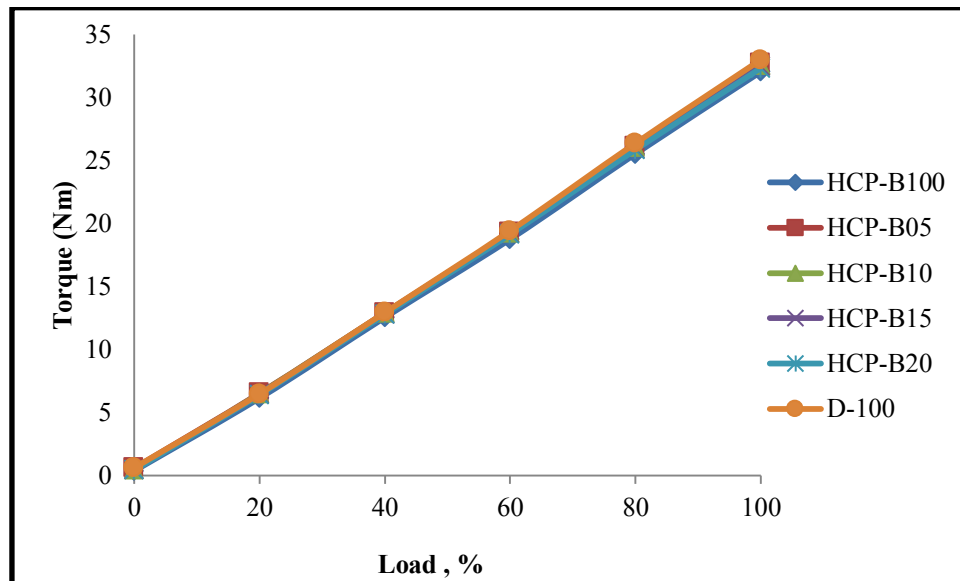
### 3. Results and discussions.

The following results are obtained by the investigation and are discussed as follows.

#### 3.1 Variation of torque with load

At the 100% engine load the HCP-B100 showed a reduction of 2.85 % in torque compared to D-100 and at the 80% engine shown a reduction of 2.65 % in torque compared to D-100. HCP-B20 shown a reduction of 2.12 % and 1.93 % in torque at max load of 100% engine load and part load of 80% engine load respectively which is shown in figure 2. The other blends lie between HCP-B20 and D-100. As expected reduction in torque is due to lower heating value of HCP-B100 than petroleum

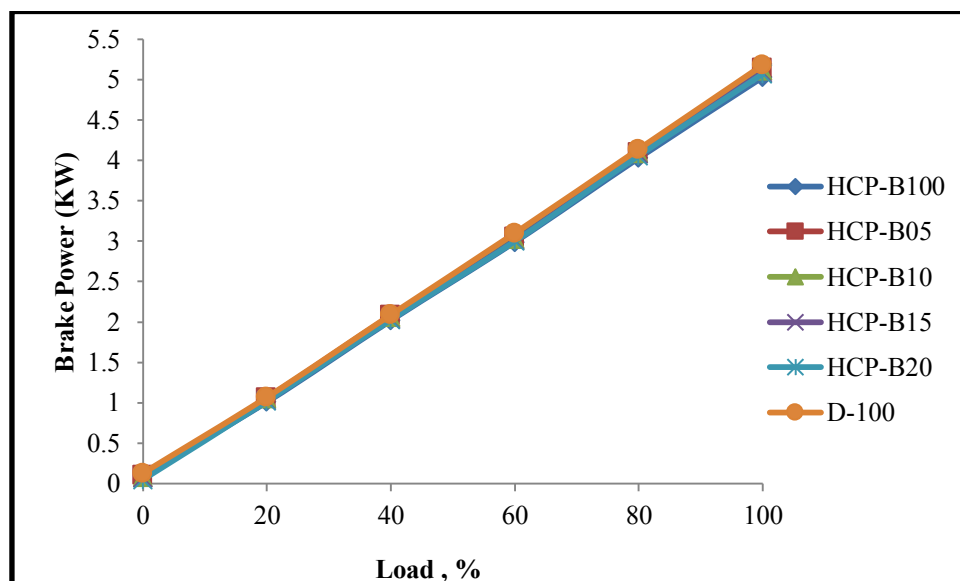
diesel. Lower calorific value of biodiesel leads to lower engine output in turn lower torque compared to diesel.



**Figure 2.** Comparison of torque with load.

### 3.2 Variation of brake power with load

The below figure 3 shows variation of BP with load. At the maximum (i.e 100%) engine load the HCP-B100 shown a reduction of 2.89 % in BP compared to D-100 and at the part (i.e. 80%) load 2.42 % in brake power. HCP-B20 shown a reduction of 1.75 % and 1.24 % at max load (100% load) at part load (80% load) respectively.



**Figure. 3** Comparison of brake power with load.

The BP of other blends lies between HCP-B20 and D100. The calorific value of HCP-B100 is lower than petroleum diesel and viscosity is higher than the petroleum diesel. Lower calorific value of

biodiesel leads to lower engine output in turn reduced BP than petroleum diesel . And higher viscosity and density leads to poor atomization and poor fuel spray characteristics which led to reduced BP.

### 3.3 Variation of brake thermal efficiency with load

Figure 4 shows BTE variation of the engine fueled with HCP Biodiesel , PD and their blends. The BTE indicates the ability of a fuel for converting its energy content into power output when fuelled in the the engine to run it. Increase in BTE with increase in load for diesel ,biodiesel and their blends is observed and also observed that at the full load HCP-B100 shown a reduction of 3.15 % in BTE compared to D100 at full load and 3.0 % at part load (80% load). HCP B-20 shown a reduction of 1.8 % and 1.4 % in BTE at full (100%) and part (80%) engine loads respectively. Brake thermal efficiencies of other blends lies between B20 and D100. BTE is lower because of lower calorific value ,higher viscosity higher density compared to PD, improper air fuel mixing, poor atomization characteristics. BTE of HCP microalgae biodiesel is lesser at higher load due to the lesser combustion time per unit fuel compared to the lower loads [9]. As the quantity of biodiesel in the blends increased the ID and combustion rate were increased. [10]

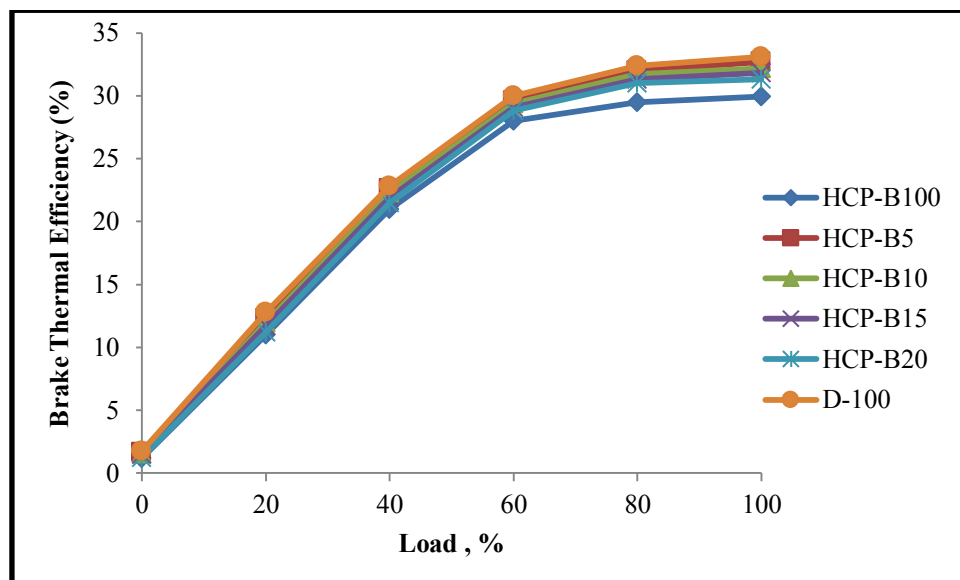
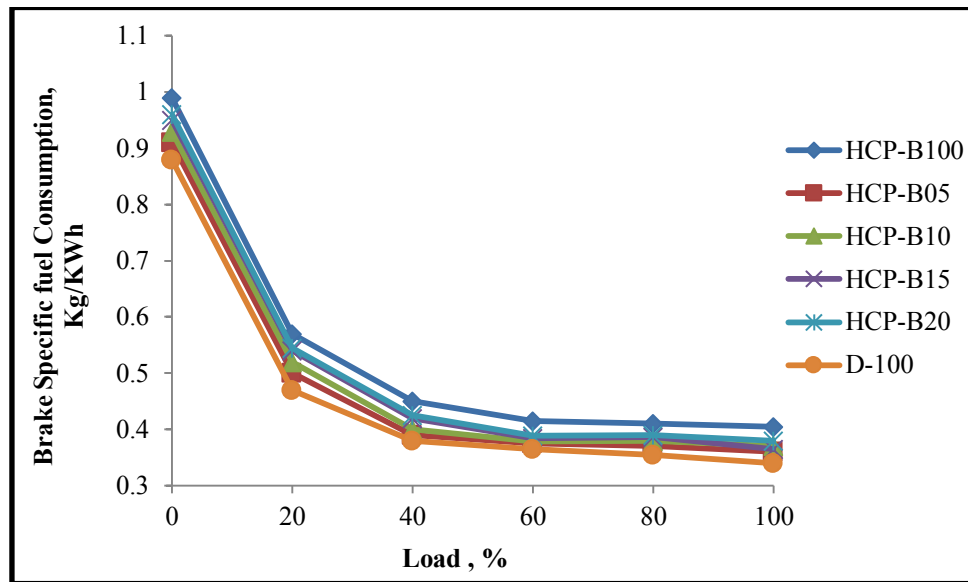


Figure 4. Comparison of brake thermal efficiency with load.

### 3.4 Variation of brake specific fuel consumption with load.

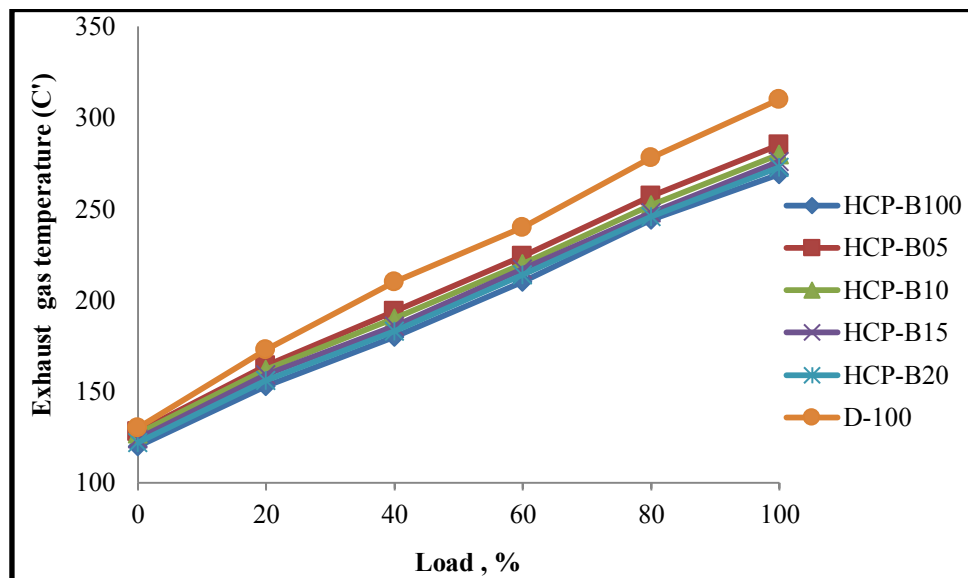
The variation of BSFC with load for biodiesel, diesel and their blends is shown in figure 5. HCP microalgae biodiesel and its blends shown higher BSFC compared to diesel higher than that of diesel over entire range of load. It is observed that at the 80% engine load ,the HCP-B100 shown an increase of 15.49 % and at the 100% engine load shown an increase of 15.96 % in Brake specific fuel consumption compared to PD. HCP-B20 shown an increase of 9.85 % and 12.04 % at the engine loads 80% and 100% respectively. Also observed that as the amount of HCP microalgae biodiesel in the blends increased the heat value of blend decreased due to lower calorific value of HCP microalgae biodiesel than that of PD. To maintain the same BP as that of the diesel, the fuel consumption is more with blends of biodiesel with diesel due to their lower calorific value. [11]. Hence, BSFC will increase with increase in percentage of biodiesel in the blends.



**Figure 5.** Comparison of brake specific fuel consumption with load.

### 3.5 Variation of exhaust gas temperature with load.

Variation of Exhaust gas temperature with load for HCP microalgae biodiesel and its blends used in diesel engine is shown in figure 6. The EGT of HCP biodiesel combustion is slightly lower than the PD and it is similar to the variation of PD, this indicates that biodiesel and diesel combustion profiles are similar and engine heat loss profiles are also similar.



**Figure 6.** Comparison of exhaust gas temperature with load.

The HCP-B100 shown a reduction of 12.23 % and 13.22 % in exhaust gas temperature compared to that of D-100 (PD) at 80% and 100% engine loads respectively. HCP-B20 shown a decrease in exhaust gas temperature by 11.51 % and 11.93 % at the 80% and 100 % engine load respectively compared to PD. This is due to higher oxygen content in the biodiesel compared to PD and which is

the main component in enhancing combustion reactions rate. Increased combustion reaction rates means complete flame propagation throughout the air fuel mixture and improved combustion [12].

### 3.6 Variation of oxygen with load.

The below figure 7 shows the oxygen variation with load in the exhaust gas for HCP micro algae biodiesel, diesel and their blends. The oxygen content in the exhaust emissions of HCP microalgae biodiesel is slightly higher than that of the PD exhaust emissions. The  $O_2$  content in exhaust for HCP-B100 increased by 13.07 % and 11.81 % compared to diesel at the 80% and 100% engine load respectively. HCP-B20 shown an increase in  $O_2$  content in the exhaust by 11.54 % and 8.18 % at the 80% and 100% engine load respectively compared to diesel. The heating value of HCP microalgae biodiesel lower than the PD due to its higher oxygen content. Hence as the percent of biodiesel content in the blends increases the energy content decreases.

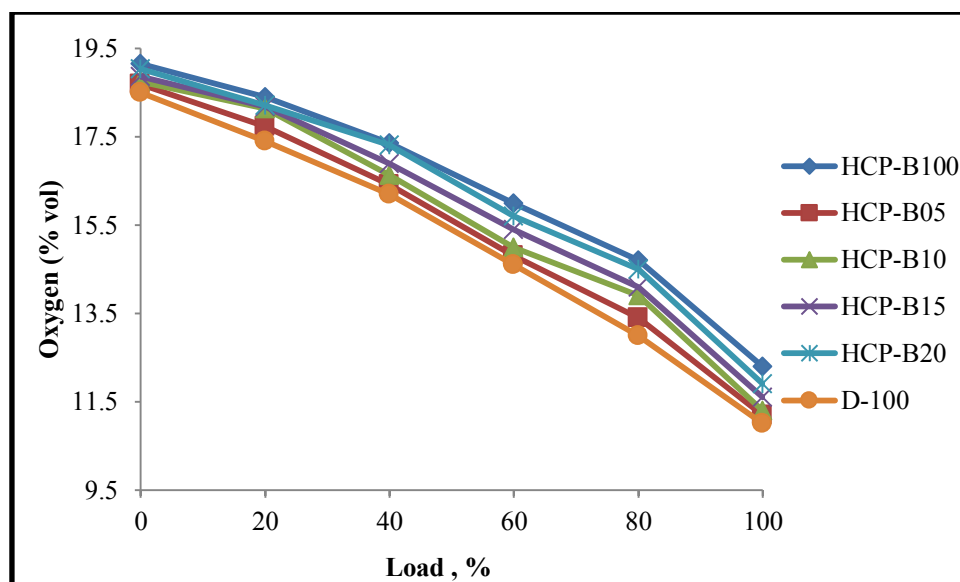


Figure 7. Comparison of oxygen variation with load.

### 3.7 Variation of cylinder pressure with crank angle

Cylinder pressure variation with crank angle inside the the engine cylinder for HCP-B100, HCP-B05, HCP-B10, HCP-B15, HCP-B20 and D100 at maximum load shown in figure 8. It is observed that peak cylinder pressure for HCP microalgae biodiesel and its blends is lower than that of the diesel. Hence as the percent of biodiesel content in the blends increases the peak cylinder pressure decreases. As the load increases the peak cylinder pressure increases. In the initial stage of combustion, the combustion proceeds at faster rate for HCP- B20 and HCP-B100 in comparison to that of diesel. It is also observed that peak pressure shifts towards TDC. There is no much of variation observed in combustion process among these fuels. Peak pressure value for HCP-B100, HCP-B20, and D-100 at maximum load is 61.40, 62.96, 64.56 bar respectively. So the decrease in peak pressure of HCP-B100 is 3.16 bar compared to D-100 at maximum load. The decrease is due to lower calorific value and higher viscosity [13]. During the initial stages of combustion, the combustion rate influences peak pressure in the compression ignition engine. Lower volatility, higher viscosity of HCP-B100, leads to improper air fuel mixing and poor atomization of fuel, ignition delay and finally reduction in peak pressure.



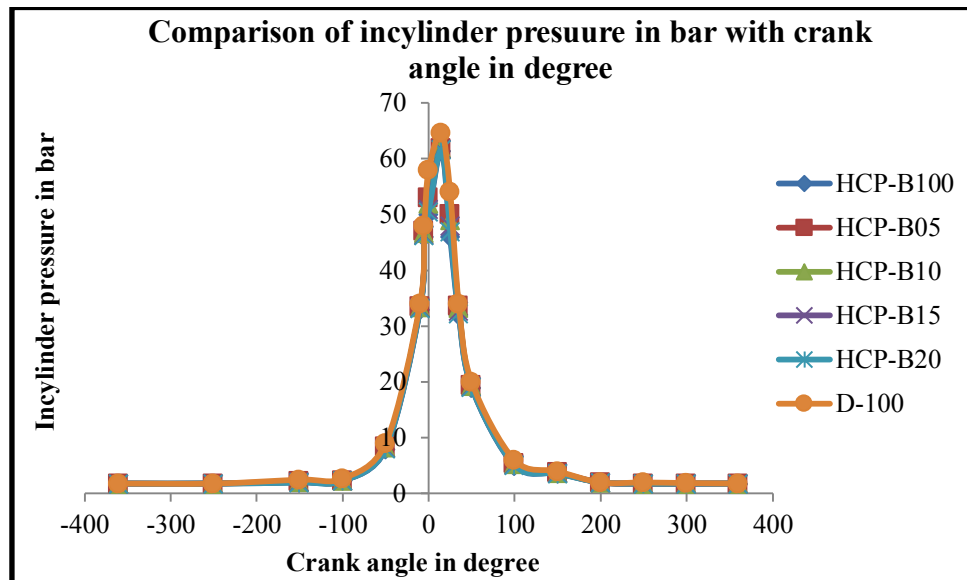


Figure 8. Variation of cylinder pressure with crank angle.

### 3.8 Variation of CO with load

Variation of CO with load for PD, HCP microalgae biodiesel and its blends with PD is shown in Figure 9. Due to incomplete combustion the CO emissions occurs. CO emissions mainly depends on air-fuel ratio and engine temperature.

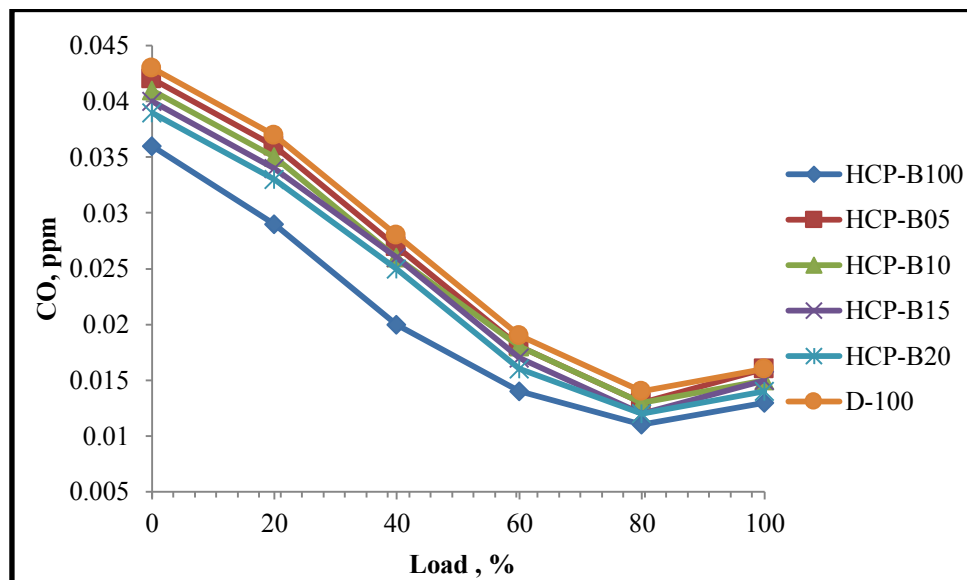


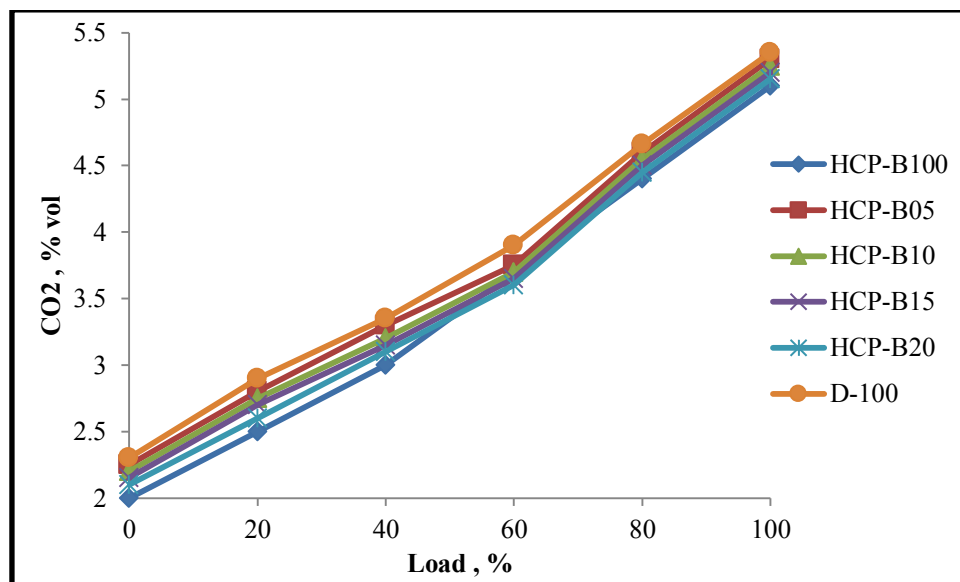
Figure 9. Comparison of CO variation with load.

At lower loads CO emissions are higher for all diesel, biodiesel and their blends, the reason for this may be incomplete combustion of fuel. At the 80% (part) load of the engine the HCP-B100 showed a reduction of 20 % and at the 100% (full) load the HCP-B100 shown a reduction of 18% in CO compared to PD. HCP-B20 showed a decrease in CO content in the exhaust by 15.87 % and 13.89 % at the 80% and 100% engine loads respectively than that of PD for the same loading conditions. Due to conversion of CO to CO<sub>2</sub> with increase in load at constant engine speed of 1500 rpm lesser CO

emissions. In the engine exhaust. The higher oxygen content present in the HCP microalgae biodiesel helps to convert more CO into CO<sub>2</sub>, in turn lower CO emissions. The oxygen accelerates the rate of combustion reactions rates [14]. Increased combustion reaction rates means complete flame propagation throughout the air fuel mixture and improved combustion of biodiesel. As the biodiesel percent in the blends increased the CO emissions lowered at any measured load.

### 3.9 Variation of CO<sub>2</sub> with load.

Figure 10 compares the CO<sub>2</sub> variation with engine load of an IC engine fuelled with HCP microalgae biodiesel, diesel and their blends and its blends used in diesel engine.



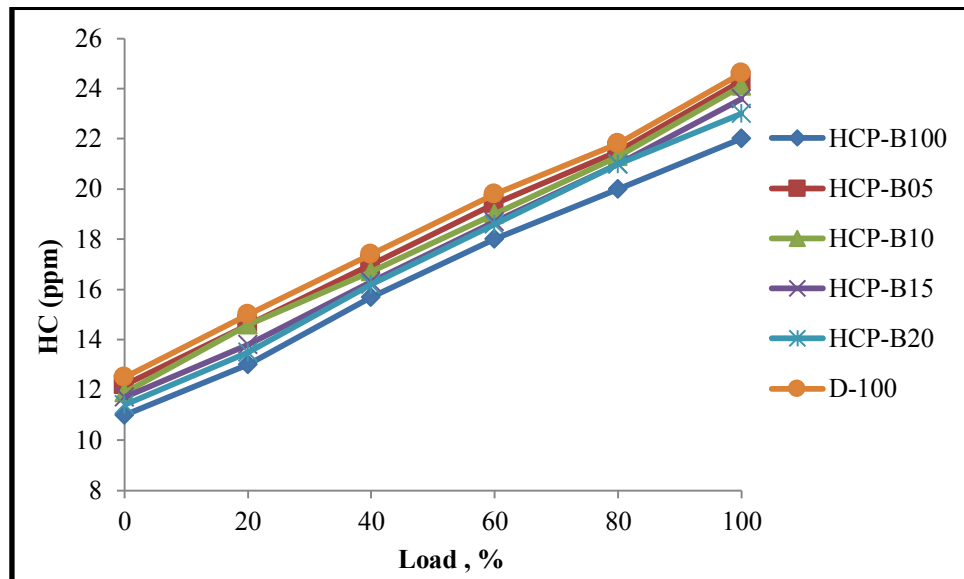
**Figure 10.** Comparison of CO<sub>2</sub> variation with load.

The HCP-B100 showed a reduction of 5.58 % and 4.67 % in CO<sub>2</sub> (% vol.) compared to that of D-100 at the 80% part load and at the 100% full load respectively. HCP-B20 shown an decrease in CO<sub>2</sub> content in the exhaust by 4.66 % and 3.73 % at the 80% part load and at 100% full load respectively compared to diesel. As the engine load increases from 80% load to 100% load the CO<sub>2</sub> emissions increases from 4.4 % vol to 5.1% vol in the exhaust emissions for HCP-B100. The CO<sub>2</sub> emissions of HCP microalgae biodiesel and their blends are lower compared to petroleum diesel for all tested loads due to the higher oxygen content of the microalgae biodiesel. This may be due to the presence of more oxygen content in the microalgae biodiesel compared to pure diesel and which propagate the flame throughout air fuel mixture in turn accelerated combustion reaction rate and improved combustion [15].

### 3.10 Variation of HC with load.

HC emissions variations with different loads are presented in figure 11. At 80% engine load. HCP-B100 shown a reduction of 8.25 % and at the 100% engine load shown a reduction of 10.56 % in HC compared to PD. HCP-B20 shown a decrease of 3.66 % at the 80% engine load and 6.50 % at 100% engine load. HC emissions are lower with the HCP microalgae biodiesel and its blends HC compared to PD because of higher oxygen content of the biodiesel. Compared to the PD the biodiesel has more oxygen and which helps in better air fuel mixing and combustion of this mixture. It is

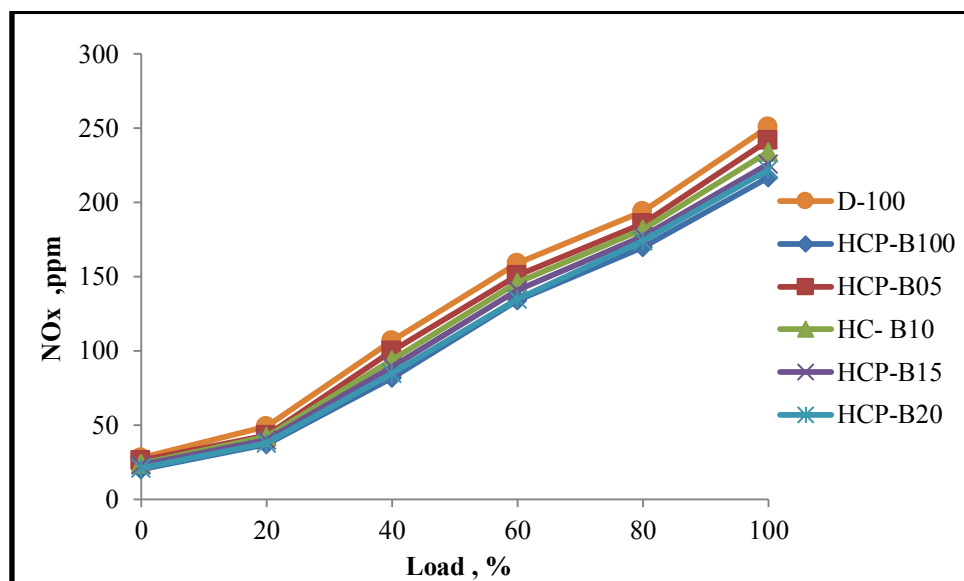
observed that the HC emissions are increasing with all the loads. At maximum loads, for a given quantity of air the amount of fuel supply is more to maintain a constant output power. Consequently, this makes the richer air fuel mixture and results in increased HC emissions.



**Figure 11.** Comparison of HC variation with load

### 3.11 Variation of $NO_x$ with load.

$NO_x$  variation with load for HCP biodiesel, diesel and their blends is shown in figure 12. Oxidation of nitrogen present in the fuel with air inside the engine cylinder during combustion of air fuel mixture leads to  $NO_x$  formation.



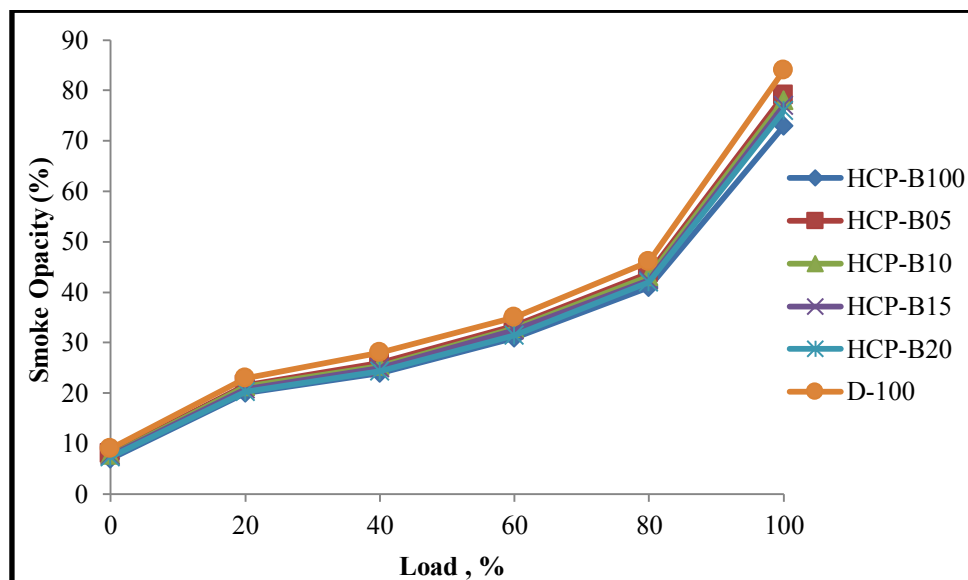
**Figure 12.** Comparison of  $NO_x$  variation with load.

It is observed that  $NO_x$  emissions are lesser with HCP microalgae biodiesel compared to petroleum diesel due to reduction in premixed combustion.  $NO_x$  formation is dependent on flame retention time,

pressure, reaction temperature, availability of excess oxygen, in the engine combustion chamber and premixed portion of combustion [16]. Major factors which influence NO<sub>x</sub> are the air fuel ratio and its peak temperature inside the combustion chamber. Heat release rate is lower due to lower calorific value of HCP-B100 and this leads to lower peak temperature, in turn reduced NO<sub>x</sub> emissions [17]. At the 80% engine load HCP-B100 shown a reduction of 12.37 % in NO<sub>x</sub> and at the 100% engine load shown a reduction of 13.54 % compared to PD. HCP-B20 shown decrease in NO<sub>x</sub> content in the exhaust by 10.30 % and 11.55 % at the 80% (part) and 100% (full) engine loads respectively compared to diesel. Compared to the NO<sub>x</sub> emissions of PD, NO<sub>x</sub> emissions of HCP microalgae biodiesel were lower because they provide lower local peak temperature and lower peak pressure inside the engine cylinder compared to the PD. The lower calorific value of HCP microalgae biodiesel leads to lower adiabatic flame temperature and lower BTE. The lower premixed combustion may be the cause for the lower NO<sub>x</sub> emissions with HCP microalgae biodiesel.

### 3.12 Variation of smoke opacity with load.

Figure 13 compares the smoke opacity variation with engine load. Smoke opacity indicates the extent of combustion of the fuel. At all the loads decrease in the smoke opacity with the use of HCP microalgae biodiesel is observed due to the heterogeneous nature of diesel combustion, air-fuel ratios, which affect smoke formation. At high temperatures and pressures, in the fuel-rich zone of the engine cylinder smoke formation occurs.



**Figure 13.** Comparison of smoke opacity variation with load

Fuel-rich regions can be reduced by the partially oxygenated supplied fuel and which in turn limits the primary smoke formation. The smoke opacity mainly depend on quantity of oxygen in the fuel and air in the cylinder. The increase in load requires more quantity of fuel injection for a constant air supply, resulting in lesser oxidation and thus smoke opacity increases. In this study, it is found that the smoke emissions decreased with blends of HCP microalgae biodiesel due to the inherent presence of oxygen in the biodiesel which stimulates reaction of oxidation and thus lower smoke emissions. At the 80% part load of the engine the HCP-B100 shown a reduction of 10.86% and at 100% full load shown a reduction 13.09% in smoke opacity compared to PD. HCP-B20 shown a decrease in smoke opacity in the exhaust by 3.52 % and 3.94 % at 80% part load and at full load (100% load) respectively compared to diesel.

#### 4. Conclusion.

Presently the fossil fuels are not considered as sustainable because they are depleting in nature and may exhaust in near future. Due to the many advantages of biofuels over the fossil fuel resources, the research and development in biofuel production has attracted much attention in recent years. Microalgae biodiesel properties are comparable with biodiesel properties and ASTM biodiesel standards. Heterotrophic *Chlorella Protothecoides* microalgae biodiesel contains almost all the common FAMES content.

From this investigation it is observed that

- The engine exhaust emissions CO, CO<sub>2</sub>, HC, NO<sub>x</sub>, EGT, smoke opacity and BTE are lesser with HCP (Heterotrophic *Chlorella Protothecoides*) microalgae biodiesel and its blends with diesel compared to the exhaust emissions of PD (petroleum diesel) due to higher oxygen content in turn better combustion of biodiesel.
- It is observed that the brake-specific fuel consumption of HCP microalgae biodiesel increased compared to that of PD because of 4.34 % lesser calorific value of pure HCP microalgae biodiesel than PD.
- The brake thermal efficiencies of all biodiesel blends and pure biodiesel were reduced due to higher fuel consumption.
- It is evident that the CO level was inversely related to the engine load and inversely related with the microalgae biodiesel blends percentage in the petroleum diesel because of the higher O<sub>2</sub> in the biodiesel, which enhanced the combustion process.

So finally it can be concluded that the HCP microalgae biodiesel and its blends can replace the PD, to lower the pollution associated with engines and to meet the global energy demand without competing with food sources for biodiesel production. The lower blends of HCP microalgae biodiesel with diesel are the best replacement for PD and technically feasible as an alternative fuel for IC engine due to much lesser sacrifice in engine power and economy.

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