Performance and Exhaust Emissions of a Diesel Engine Burning Algal Biodiesel Blends

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***Abstract*--** **The production of biodiesel from algae is one of the promising alternative fuel for diesel engines. Algae oil was extracted from microalgae *Scenedesmus obliquus*. The biodiesel was produced from algal oil by transesterification. Biodiesel blends of 10 and 20% were prepared. Fatty acid analysis showed that fuel properties of *S. obliquus* were highly affected by fatty acids composition. Chemical and physical properties of biodiesel blends B10 and B20 were close to diesel oil. The performance parameters and exhaust emissions of a diesel engine burning biodiesel blends and diesel fuels were studied. Biodiesel blend B20 showed decrease in specific fuel consumption, exhaust gas temperature and increase in thermal efficiency compared to B10 and diesel fuels. There were reductions in the emissions gas for B20 compared to B10 and diesel fuels. It could be concluded that a high quality of biodiesel could be produced from microalgae *S. obliquus* and used efficiently and environmentally safe in conventional diesel engine.**

***Index Term*--** **Microalgae- Biodiesel- Fuel properties- Engine performance- Exhaust emissions.**

1. Introduction

Biodiesel as an alternative energy source has recently received more attention due to the depletion of fossil fuels and pollution problems. Biodiesel is produced from different vegetable oils and used cooked oils [1-5].

Microalgae are considered good source for fuel production due to their higher growth rate, higher yield and higher oil content in comparison with other sources [2, 6-11].

The production of biodiesel from algal oil is one of the most important renewable energy sources [12]. In vehicles, biodiesel can be used when blended with fossil diesel fuel. Tests carried out on engine recommended using blends with diesel oil up to 20% [13]. Microalgae biofuels are highly biodegradable and free of sulfur. The rest of algal cells left after extracting the oil can be used for nutraceuticals production [14, 15, 16].

High content of sulfur in diesel fuels are harmful for the environment because sulfur is oxidized to sulfur dioxide and sulfur trioxide that in presence of water convert to sulfuric acid [9]. The same authors evaluated algal biodiesel blend on a diesel engine compared to diesel fuel and they found that there was a decrease in thermal efficiency and increase in specific fuel consumption for biodiesel blends. Biodiesel blends had reductions in the harmful gases emissions compared to diesel fuel [10, 11]. Performance and exhaust emissions of a diesel engine run on blends of biodiesel Jatropha with diesel fuel. Engine performance was improved and harmful exhaust emissions were reduced. Combustion characteristics of biodiesel are near to diesel fuel. Biodiesel blends reduced smoke opacity, particulate matters, unburned hydrocarbons, carbon dioxide and carbon monoxide emissions but nitrogen oxide emissions were increased. An experimental investigation was run to evaluate the performance and exhaust emissions of a single cylinder, air cooled, four stroke, direct injection diesel engine fueled with biodiesel Jatropha and its blends (B20, B40, B60, B80 and B100) with diesel fuel. Lower blend of biodiesel (B20) is a best alternative fuel at full load condition [17]. Generally, waste cooking oil biodiesel led to a reduction of HC and CO emissions but an increase in NOx emission [18]. Performance and emissions of a diesel engine fuelled with castor biodiesel blends and pure diesel fuel separately was experimentally investigated at various engine loads. B15 and B20 biodiesel blends at full load gave the best brake specific fuel consumptions (BSFC) of diesel engine. At these conditions, increase of NOx is about 4% compared to diesel fuel [19]. Biodiesel caused reductions in engine torque and power, but the lower emissions in carbon dioxide, carbon monoxide was produced as compared to diesel fuel with an increase in NOx emissions compared to diesel fuel [20].

The aim of the current work is to evaluate the effect of biodiesel blends produced from microalgae *S. obliquus* on performance parameters and exhaust emissions of a diesel engine compared to diesel fuel.

2. Materials and Methods

2.1 Microalgae Cultivation

A culture of fresh water microalgae *Scenedesmus obliquus* was cultured on BG11 medium adapted for freshwater algae. The stock solutions were prepared from the chemicals presented in Table 1 [21].

Table I
BG11 media

BG11 Nutrient Composition	
Macronutrient	**mg/L**
$NaNO_3$	1500.00
K_2HPO_4	40.00
$MgSO_4$	75.00 ($7H_2O$)
$CaCl_2$	36.00 ($7H_2O$)
Citric Acid	6.00
Na_2CO_2	20.00
Na_2EDTA	1.00
Ferric Ammonium Citrate	6.00
Micronutrient	**g/L**
H_3BO_3	2.86
$MnCl_2.4H_2O$	1.81
$ZnSO_4.7H_2O$	0.222
$Na_2\ MoO_4.2H_2O$	0.39
$CuSO_4.5H_2O$	0.079
$Co(NO_3)_2.6H_2O$	0.0494

The culture temperature was 22±3°C. Fluorescent light was used to supply constant light intensity for the culture which was not less than 2500 lux. The microalgae was grown in 5 Liters flasks, the culture was grown for three days then harvested and the whole biomass was transferred to a photo bioreactor containing 400 liters of BG11 media as shown in Figure1. The cultures were supplied with air using an air pump to generate large, slow bubbles to mix the culture and increased the contact of the culture with air and the medium. The microalgae cells were harvested by settling, and then the settled biomass was subjected to centrifugation at 2000 rpm for 10 min. The collected biomass was dried at 60ºC [21].

Fig. 1. Photo bioreactor for growing *Scenedesmus*.

2.2 Lipid Extraction

The biomass of microalgae was dried and ground into homogenous fine powder. The dry cells were mixed with Hexane and Isopropanol with the ratio of 3:2 (v/v) as co solvent. The homogenate mixture was subjected to a magnetic stirrer at 30°C for 2hr. Cell residue was removed by filtering. The filtrate material was transferred into a separating funnel and sufficient water was added to induce biphasic layering. After settling, the solvent mixture was partitioned into two distinct phases, top dark green hexane layer containing most of the extracted lipids and bottom light green layer containing most of the co-extracted non lipids. The hexane layer was collected in a preweighted flask and evaporated using a rotary evaporator [22]**.**

2.3 Biodiesel preparation

Biodiesel production was produced by transesterification process. The reaction was carried out using H_2SO_4 acid (98%) as a catalyst (100% in relation to the mass of lipid). Methanol was added and the ratio of alcohol/lipid was 30:1 (volume/weight). Half of the methanol volume was previously added in order to dissolve the oil then the other volume of methanol mixed with H_2SO_4 and the whole sample. The reaction was performed at 60°C for 4 hr. under constant stirring in a water bath under reflux. After complete reaction, the excess alcohol is removed by evaporation using a rotary evaporator. The hexane was added to the reaction mixture as a nonpolar solvent. The mixture was transferred to a separating funnel and left to be settled. After settling, the mixture was partitioned into two distinct phases: an upper hexane layer containing mostly fatty acid methyl ester (FAME) and a bottom layer containing the glycerol and pigments [23].

2.4 Fuel properties

Algae biodiesel blends B10 and B10 properties were analyzed at the Egyptian Petroleum Research Institute, Cairo, Egypt according to standard test procedures. The measured physical and chemical properties like density, viscosity, flash point, cetane index and heating values were comparable with those of diesel fuel.

2.5 Identification of fatty acid methyl esters by GC

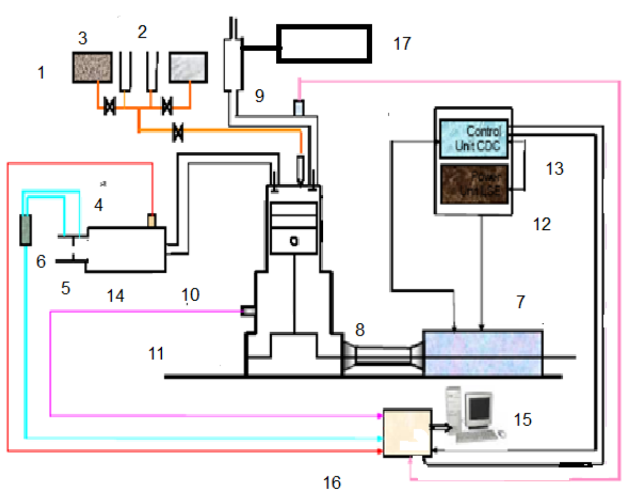
The fatty acid methyl esters were performed using a GC HP 6890. The GC supported with flame ionization detector (FID). GC HP 6890 was equipped with 5% HP5 (phenyl methyl siloxane), capillary columns of length 30µm, diameter 320 µm and 0.25 µm film thickness. The oven temperature was prepared at an initial temperature of 70°C to 250°C as a final temperature at an increasing rate 4 °C/min. The injector was set at 250°C. Gas flow rates were N: 30 ml/min, Helium: 30 ml/min and air: 300 ml/min. The quantification of all the identified components was prepared based on the composition of their relative retention time.

2.6. Experimental Test Rig

The study was carried out to investigate the effect of biodiesel blends B10 and B20 on performance and exhaust emissions of a diesel engine and compared to diesel fuel. Schematic diagram of a diesel engine test rig is shown in Fig.2. The tested engine was Kirloskar make, single cylinder, four stroke, water cooled and direct injection diesel engine. Its specifications were given in Table II. This engine was connected to an eddy current dynamometer to measure the engine speed and load. The engine was equipped to measure fuel consumption, engine speed and exhaust gas temperature. This engine received air through an air box fitted with an orifice for measuring air consumption. A pressure differential meter was used to measure the pressure difference between the two sides of the orifice. Fuel consumption rate was measured using a glass burette and stop watch. Tested engine speed was measured using a digital tachometer. MRU DELTA 1600-V exhaust gas analyzer was used for measurement of exhaust emission concentrations of CO, HC, CO_2 and NO_x. The schematic diagram of experimental set up was shown in Fig.1. The engine was warmed up before taking all readings. The measurements were recorded after the engine reached its stable condition. The engine was operated with blends of diesel fuel and algal oil biodiesel blends of B10 and B20. At every engine load, the engine speed was maintained constant at rated speed of 1500 rpm. Performance parameters were studied such as specific fuel consumption, thermal efficiency, exhaust gas temperature, volumetric efficiency and air- fuel ratio. Exhaust emissions concentrations were recorded such as CO_2, CO, NO_x and HC.

Table II
Test Engine Specifications.

Engine parameters	Specifications
Type	Kirloskar
Number of cylinders	Single
Cycle	Four stroke
Cooling	Water cooled
Cylinder diameter (mm)	85
Piston stroke (mm)	110
Compression ratio	17:1
Rated speed	1500 rpm
Maximum output power	6.5 hp



1- Diesel Tank	10- Oil temperature sensor
2- Biodiesel Tank	11- Diesel engine
3- Burette	12- Power unit
4- Intake air temperature sensor	13- Control unit
5- Orifice	14- Air tank
6- Pressure differential sensor	15- Personal computer
7- Eddy current dynamometer	16- Data acquisition card
8- Cardan shaft	17- Exhaust gas analyzer
9- Exhaust temperature sensor	

Fig. 2. Schematic Diagram of diesel Engine test rig burning diesel and biodiesel blends fuels.

3. Results and discussion

3.1 Fatty acid composition

The fatty acid profile of *S. obliquus* is presented in Table 3. The results indicated that the chain length of *S. obliquus* is ranged from C14 to C18. Both saturated and unsaturated fatty acids were detected (33 and 67%, respectively). The results revealed that percentage of myristic acid (14:0) 3%, palmitic acid was (C16:0) 23.4% and Stearic acid was (C18:0) 3.4%. However the unsaturated fractions were detected as C16:1, (Palmetoleic acid methyl ester, 7.1%), C18:1 (Oleic acid methyl ester, 17.4%), C18:2 (Linoleic acid methyl ester 19.4%), and C18:3 (Linolenic acid methyl ester 23.1%). These results are in agreement with these references [24, 25, 26]. They found that the oils extracted from *Chlorella* and *Scenedesmus* were composed of unsaturated fatty acids (50-65%). Oils with high oleic and palmitic acids content have been found to have a good quality of fuel.

Table III
Fatty acid composition of Biodiesel from *Scenedesmus obliquus*

Fatty acids	Percentage (%)
C14: 0	3
C16: 0	23.4
C16: 1	7.1
Total C 16	30.5
C17: 0	3.2
C18: 0	3.4
C18: 1	17.4
C18: 2	19.4
C18: 3	23.1
Total C18	63.3
Lipid Criteria	
Total Saturated (TS)	33
Total mono unsaturated	24.5
Total polyunsaturated	42.5
Total unsaturated (TU)	67
TS/TU	0.5

The results in Table (III) showed also that the unsaturated fatty acids with four or more double bonds are not detected. These double bonds are susceptible to oxidation and consequently reduce the acceptability of microalgae oil for the production of biodiesel. The fatty acid composition of *S. obliquus* showed high value of palmitic acid (23.4%) and oleic acid (17.4%) which met the requirements of European legislation for biodiesel. Viscosity increases with increasing fatty acids chain length and degree of saturation. The atomization of fuel in combustion chamber is highly affected by viscosity of the biofuel and resulted in deposits formation (23). It could be concluded that the saturated and long chain length fatty acids produce a biodiesel with good stability and higher cetane number [27, 28].

3.2 Physical and Chemical properties of fuels

The results given in Table 4 showed that physical and chemical properties of biodiesel blends like density, viscosity, flash point, cetane index and heating values were comparable with those of diesel fuel. Table 4 listed the main fuel properties and ASTM standards of 10 and 20% blends as compared to diesel fuel and ASTM standards. It is clear that the viscosity of algal biodiesel blends B10 and B20 were higher than diesel fuel, however, it was fit with ASTM standards values. More viscous fuel is generally unsuitable for use in diesel engines due to inefficient atomization. However the heating values of B10 and B20 biodiesel blends were within the acceptable limit of diesel fuel. The flash point of *S. obliquus* biodiesel blend B10 and B20 are higher than diesel fuel and its values were 83, 90 and 73°C, respectively. This makes the biodiesel fuel safer during handling and storage than diesel fuel. In addition, cetane number of biodiesel blend B10 and B20 were 56 and 70, respectively which were higher than the minimum requirement of diesel fuel (69). Therefore it is expected that fuel quality and combustion efficiency will be higher than that of diesel fuel. It could be concluded that the fuel properties of *S. obliquus* biodiesel is almost within the acceptable recommended limits. Similar results were obtained by Ahmed et al [29]. They produced biodiesel from *Chorella vulgass* oil and the produced biodiesel was analyzed for viscosity of 4.9 mm^2/s, flash point of 160°C, specific gravity of 0.91 g/ml and cetane number of 51 min. Properties of *S. obliquus* biodiesel was compared with ASTM standards and it was found with high quality biodiesel.

Table IV

Physical and chemical properties of biodiesel blends B10 and B20 compared to diesel fuel and ASTM standards.

Properties	Method	ASTM D-6751-02 Standard	Diesel oil	Algal Biodiesel (B10)	Algal Biodiesel (B20)
Density @ 15.56°C	ASTM D-4052	0.88	0.8378	0.8405	0.8438
Kinematic viscosity, cSt, @ 40° C	ASTM D-445	1.9-6.0	1.91	3.31	5.99
Flash point, °C	ASTM D-93	>130	73	83	90
Cetane Index	ASTM D-976	> 47	68.75	56	69.69
Gross Calorific value KJ / Kg	ASTM D-224	--------	44401	42644	40486
Net Calorific value KJ / Kg	ASTM D-224	----------	41670	40017	37866

3.3 Diesel engine performance and exhaust emissions

Figure 3 showed that specific fuel consumption as effected by engine load for biodiesel blends. A decrease was shown in specific fuel consumption with the increase in engine load for biodiesel blends because of fuel consumption increase with engine brake power. Specific fuel consumptions for biodiesel blends were lower than diesel fuel. Density and lower heating value of biodiesel blends were near to diesel fuel. Specific fuel consumption of algae biodiesel blend B20 achieved maximum decreases about B10 and diesel fuel by about 7 and 10%, respectively. The changes of specific fuel consumption for biodiesel blends B10 and B20 were insignificant. These results were confirmed by these references [10, 30].

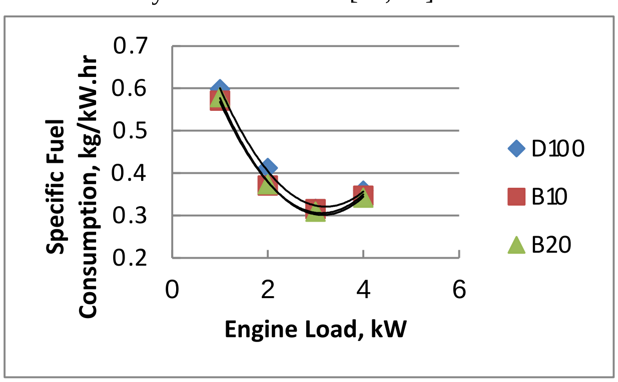


Fig.3. Variation of Specific Fuel Consumption with Engine Load for biodiesel blends

Figure 4 studied the effect of engine loads on the thermal efficiency of biodiesel blends. Thermal efficiency increased with the increase in engine brake power because of heat loss decrease and with engine load increase. Thermal efficiencies for B10 and B20 were higher than diesel fuel. Thermal efficiencies increase of biodiesel blends compared to diesel fuel was due to decrease of fuel consumption. The maximum increase of thermal efficiency for B10 and B20 about diesel fuel was 7.5 and 15%, respectively at full load. The above results were in agreement with the results reported by these references [10, 11].

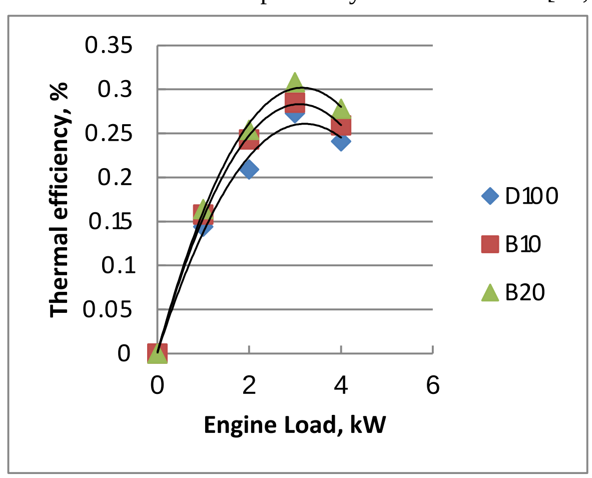


Fig. 4. Variation of Thermal Efficiency with Engine Load for biodiesel blends.

Figure 5 showed that exhaust gas temperature increased for all biodiesel blends as engine load increased due to increase of fuel consumption and heat loss in exhaust gases. Exhaust gas temperatures for biodiesel blends B10 and B20 were lower than diesel fuel. This was due to decrease of fuel consumption, higher thermal efficiencies and lower heat loss in exhaust gases of biodiesel blends. Values of exhaust gas temperatures for diesel and biodiesel blends B10 and B20 were 305, 294 and 250°C at full load, repectively. The deviations of exhaust gas temperatures for biodiesel blends were insignificant. These results were confirmed by references [11, 12].

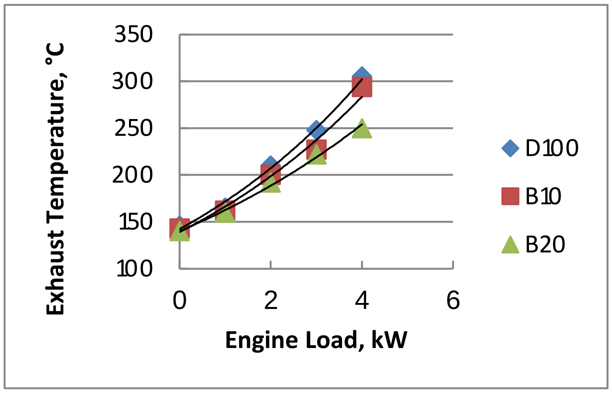


Fig. 5. Variation of Exhaust Gas Temperature with Engine Load for biodiesel blends.

The effects of engine load on air- fuel ratios for biodiesel blends were investigated in Fig.6. Air- fuel ratios decreased with the increase in engine loads due to the increase in fuel consumption and the richer mixture at higher loads. Fuel consumptions were lower for biodiesel blends B10 and B20 compared to diesel fuel hence air-fuel ratios increased. Maximum increases in air- fuel ratio of algae biodiesel blend B20 about B10 and diesel fuel by about 9 and 11%, respectively.

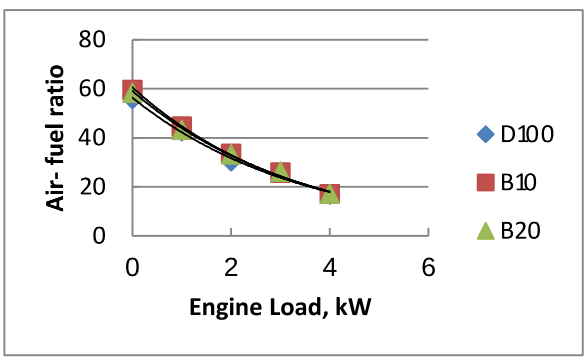


Fig. 6. Variation of Air- Fuel Ratio with Engine Load for biodiesel Blends.

Figure 7 showed variations of volumetric efficiency with engine load. Volumetric efficiency decreased with the increase in engine load. This was due to air density decrease associated with higher engine temperature at higher loads. Volumetric efficiencies biodiesel blends B10 and B20 were lower than diesel fuel. Volumetric efficiency of algae biodiesel blend B20 produced maximum decreases about B10 and diesel fuel by about 12 and 17%, respectively.

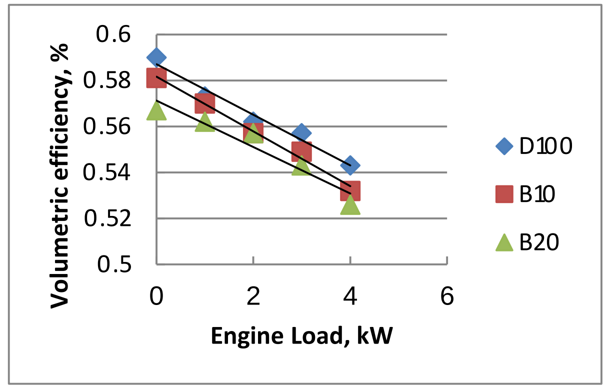


Fig. 7. Variation of Volumetric Efficiency with Engine Load for Biodiesel Blends.

The amount of CO_2 emissions increased with the increase of engine load as shown in Fig.8. This was due to increase in fuel consumptions at higher engine loads. Lower percentages of CO_2 emissions were produced for biodiesel blends compared to diesel fuel. There were reductions in CO_2 emissions for biodiesel blends B10 and B20 about diesel fuel due to the lower percentage of C/H ratio in biodiesel blends. The oxygen content in biodiesel blends led to combustion improvement. B20 blend showed maximum decreases in CO_2 emission about B10and diesel fuel by about 5 and 8%, respectively. The above results were in agreement with these references [31, 32].

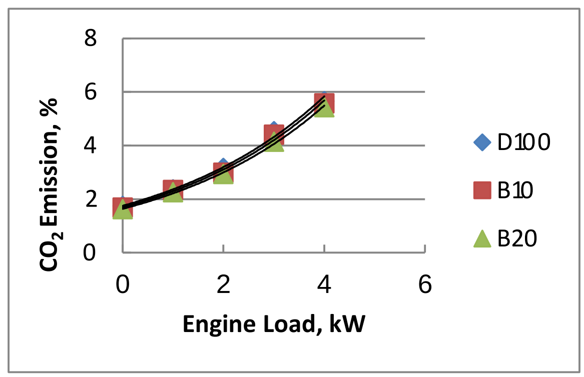


Fig. 8. Variation of CO_2 Emission with Brake Power for biodiesel blends

CO emissions of biodiesel blends B10 and B20 were explained in Fig.9.CO emissions decreased with the increase in engine load from lower loads to medium loads and increased in higher loads. The higher combustion temperature at lower engine loads led to the decrease of CO emission. Decrease of CO emissions for biodiesel blends was due to more oxygen molecules in biodiesel blends compared to diesel fuel. Oxygen molecules in biodiesel enhanced vaporization and atomization of biodiesel blends compared to diesel fuel. Maximum decreases in CO emission of algae biodiesel blend B20 about B10 and diesel fuel by about 15 and 19%, respectively. The above results were closer to the results reported by these references [11, 30, 32].

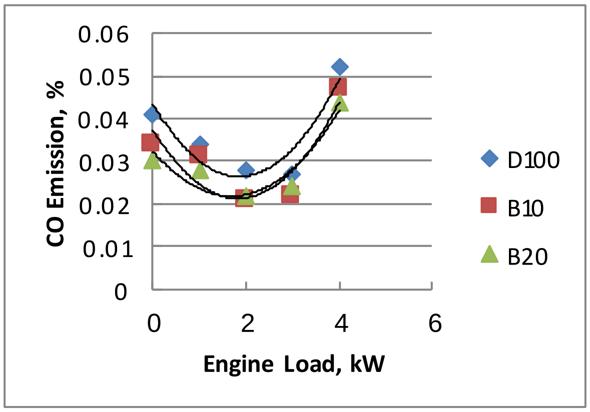


Fig. 9.Variation of CO Emission with Engine Load for biodiesel blends.

HC emissions of biodiesel blends were displayed in Fig.10. At higher engine load, HC emissions increased due to increase of fuel consumption. HC emissions of biodiesel blends were lower than diesel fuel. The maximum concentrations of HC emissions were 13, 10 and 9 ppm for diesel, B10 and B20 biodiesel blends, respectively. The above results were closer to the results reported by these references [10, 11, 30, 31, 33, 34].

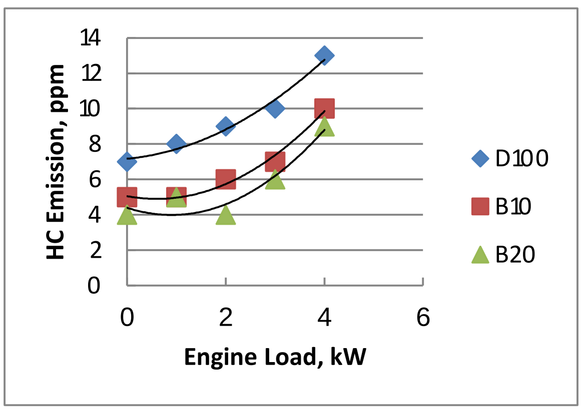


Fig. 10. Variation of HC Emission with Engine Load for biodiesel blends.

Figure.11 explained NO_x emissions variations with engine load for biodiesel blends B10 and B20. NO_x emission increased as the engine load increased because of higher combustion chamber temperature and higher fuel consumption. NO_x emissions of biodiesel blends B10 and B20 decreased about diesel fuel due to lower fuel consumptions and combustion chamber temperatures. NO_x emission formation depends on oxygen inside the combustion chamber, combustion flame temperature and reaction time. The higher cetane number led to the lower NO_x emission. Higher cetane number caused lower ignition delay, shorter duration of premixed combustion, lower rise of combustion pressure and lower NO_x emission. The maximum concentrations of NO_x emissions at full load were 356, 353 and 329 ppm for diesel, B10 and B20, respectively. The above results were in agreement with references [10, 11].

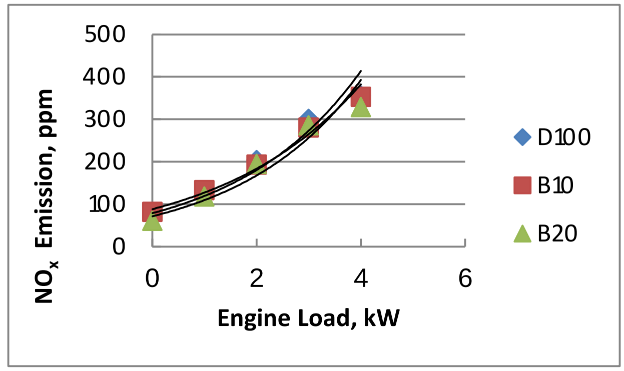


Fig. 11.Variation of NO_x Emission with Engine Load for biodiesel blends.

4. Conclusion

The results of the current work showed that the physical and chemical properties of biodiesel were accordance with standard limits. Therefore, it can be blended with diesel fuel. It could be concluded that the biodiesel produced from *S. obliquus* is environmentally friendly and showed high performance compared to diesel fuel and could be used up to 20% in diesel engine.

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