

Performance Evaluation of a Diesel Engine Using Biodiesel

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Abstract

This article is a comparative study of use of mineral diesel and biodiesel derived from cotton seed oil of Pakistani origin. The main problems associated with biodiesel are, its very high viscosity and specific gravity, which are due to long chain triglyceride esters with free fatty acids. The esters are converted into simple structure mono-glyceride esters via transesterification process. The experiments were carried out using blends of diesel and biodiesel with different ratios, to investigate the performance characteristics of engine and exhaust emissions. The experimental results show that the engine using B100 resulting in about 10% higher brake specific fuel consumption and about 10% lower brake thermal efficiency as compared to the use of B0. The engine emissions were almost free from SO_x, having reduced amount of CO, CO₂, and THC, but having higher amount of NO_x, when B100 was used as fuel. The fuel is becoming more popular due to the reduction in nasty pollutant emissions.

Key Words: Cotton Seed Oil; Biodiesel; Exhaust Emissions; CI Engines

Nomenclature

Bn	: n% Biodiesel and (100-n)% Diesel
BSFC	: Brake Specific Fuel Consumption
BTE	: Brake Thermal Efficiency
CI	: Compression Ignition
CO	: Carbon Monoxide
CO ₂	: Carbon Dioxide
CSO	: Cotton Seed Oil
CSOME	: Cotton Seed Oil Methyl Ester
DI	: Direct Injection
FC	: Fuel Consumption
KOH	: Potassium Hydroxide
NaOH	: Sodium Hydroxide
NO _x	: Oxides of Nitrogen
PAH	: Polycyclic Aromatic Hydrocarbons
PM	: Particulate Matter
rpm	: Revolution per Minute
SO _x	: Oxides of Sulfur
THC	: Total Hydrocarbon

1. Introduction

The rising cost of mineral diesel is becoming heavy burden on the economy of the poor countries like Pakistan, which spends major percentage of its budget to the import of diesel, which is continuously increasing due to increase in demand in transportation, industrial, and power sectors.

The increase of pollutant gasses has become another major problem, which causes increase in

green house effect, global warming, weakening of ozone layer, and acid rains. These are responsible, one way or the other, for damaging the respiratory system, nervous break down, skin diseases, and mutagenic [1].

Vegetable oil is an alternative fuel which is becoming hot favorite nowadays, as it seems to be a good solution of reducing the pollutant emissions.

In 1912, Sir Rodulf Diesel used neat peanut oil as fuel in his own designed diesel engine. He had firm belief that the vegetable oil would be the future fuel [2]. The researchers kept on working to use vegetable oils as fuel but their higher specific gravity and viscosity were the main hurdles in their further development. The discovery of huge reservoirs of petroleum, and their smooth combustion and higher thermal efficiency slowed down the research towards the use of vegetable oils. The mineral oil crises in 1970's, awareness of ruining of environment, invention of efficient techniques of vegetable oil extraction, and conversion of vegetable oils into biodiesel by chemical processing, once again, diverted the attention of the scientists towards the use of vegetable oils.

There is much reduction in CO, CO₂, and total hydrocarbon (THC) emissions from compression ignition (CI) engines by using biodiesel [3]. As the biodiesel is free from sulfur contents, so the exhaust emissions of CI engines are almost free from sulfur oxides.

Pakistan is an agriculture country. The main crops of Pakistan are wheat, rice, maize, sugarcane and cotton. In 2008-09, the cotton was cultivated on 2.82 million hector land and about 2.573 million metric ton cotton was produced [4]. A huge amount of oil can be produced from this feedstock which can be converted into biodiesel to supplement the diesel fuel; hence a lot of foreign exchange can be saved.

2. Literature Review

Biodiesel is a renewable, nontoxic, biodegradable and environment friendly fuel which can be obtained from vegetable oils and animal fats. It can be used in all types of compression ignition engines directly or in the blended form. The engine run by biodiesel exhibits the reduced amount of pollutant gasses such as soot, THC, CO₂, CO, particulate matter (PM), oxides of sulfur (SO_x), carcinogenic polycyclic hydrocarbons, and polycyclic aromatic hydrocarbons (PAH) [5, 6, 7, 8, 9]. Biodiesel is an oxygenated fuel, so its combustion is better than that of mineral diesel resulting in lower harmful pollutant emissions than mineral diesel [10].

Many of the researchers reported that there was an increase in specific fuel consumption (SFC) and decrease in brake thermal efficiency (BTE) when the engines were fed with biodiesel (methyl or ethyl ester) derived from different sources of vegetable oils, which is due to their lower calorific values [11, 12, 13].

Cherng-Yuan Lin and Hsiu-Au Lin studied the characteristics of exhaust emissions of a diesel engine using blended fuel (biodiesel and diesel), and reported that there was an increase in BSFC and NO_x but decrease in CO and CO₂, as the ratio of biodiesel was increased in the blends [14]. Goodrum and P. Geller claimed that the biodiesel has better lubricity which ultimately enhances the engine life [15].

Ejaz and Younis reviewed the use of biodiesel derived from different types of vegetable oils and concluded that the properties of cotton seed methyl ester are comparable to that of diesel, so it is encouraging to use it as a fuel in CI engines without any modification [16].

2.1 Use of Cotton Seed Oil

Cotton seed oil (CSO) consists of triglyceride, diglyceride and monoglyceride esters possessing high molecular mass (852) that is the cause of its high viscosity which resists the flow particularly when it passes through the injection system [17]. Although the raw oil can be used as fuel in CI engines, yet it is not

successful for long term running of engines. However, the oil can be used as an alternative fuel after processing it chemically, by which the viscosity and specific gravity is reduced. A number of chemical processes are used to convert the raw oil into biodiesel. The most common method among them is transesterification [18].

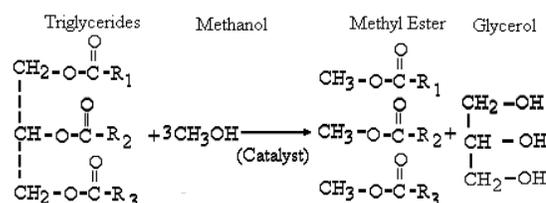
Goering et al. determined the characteristics of some vegetable oils, including cotton seed oil, and reported that CSO is also a candidate fuel [19].

Md. Nurun Nabi et al. developed the biodiesel from CSO and tested it in a 4-stroke, single cylinder, water-cooled, naturally aspirated, direct injection (DI) diesel engine and concluded that there was a reduction of 14% smoke and 24% particulate matter (PM) when it was fueled with a blend of 10% biodiesel and 90 % diesel (B10). CO reduced by 24% while NO_x increased by 10% when the engine was fueled with B30 [8].

Y. He and Y. D. Bao conducted the experiments using blends of diesel and CSO in various ratios and concluded that CSO can be one of the best alternative fuels up to 30% CSO and 70% diesel. Its calorific value is higher as compared to many other vegetable oils. They also concluded that for the highest efficiency the appropriate injection angle was 22°, i.e. advanced by 3 to 5° as compared to pure diesel [20].

3. Transesterification of Cotton Seed Oil

Transesterification is the process by which the heavier molecules of vegetable oils or animal fats, which consist of mainly tri-glyceride, are converted into mono-glyceride. In this process, the oils are reacted with methanol or ethanol in the presence of acid or base catalysts. Reaction equation of transesterification process is



where R₁, R₂, R₃ are the Hydrocarbons (C_nH_{2n+1}), the value of n is different for different feed stock, more commonly 17 to 19.

Three moles of methanol react with one mole of vegetable oil to form three moles of mono-glyceride (methyl ester) and one mole of glycerol.

Table 1: Properties of Biodiesel

Property	Units	Diesel	CSO	CSOME	Standard	Equipment
Density at 25 °C	Kg/liter	0.84	0.90	0.88	D 4052-96	Relative density bottle
Viscosity at 25 °C	mm ² /sec	3.7	31.5	4.2	D 445-03	Bath Viscometer
Calorific Value	MJ/kg	42.0	41.0	38.5	D 240-02	Bomb Calorimeter
Flash Point	°C	74	285	220	D 93-02a	Pensky martens closed cup

Generally, base (NaOH or KOH) catalysts are used, to increase the reaction rate, as compared to acid catalysts. After the completion of reaction, mono-glyceride ester and glycerol are separated, from which the mono-glyceride ester (biodiesel) can be used as fuel.

3.1 Preparation of Biodiesel

Five liters of CSO was obtained from local market. Oil was filtered by using double layer cotton cloth to remove the solid particles and other impurities.

Twenty five grams lye of sodium hydroxide (NaOH) was mixed in one liter methanol (20% of oil) and stirred vigorously to get homogenous mixture, called sodium methoxide, which was poured in a transparent tank. The methanol was preferred over ethanol due to its lower cost, higher solubility, and fast reaction rate with the oil.

The CSO was heated up to 65°C and poured in the tank, which already contained sodium methoxide. Both of the fluids were agitated continuously for two hours and allowed to cool and settle. After about an hour the thick, dark brown gel type fluid (glycerol) started settling in the bottom of the tank. The level of glycerol went on increasing till six hours. It seemed that the reaction and settling was completed in six hours, however to make certain, it was allowed to settle for further two hours. The light pale blackish fluid (biodiesel) was found floating above the gel (glycerol). Both were separated gravitationally in two different vessels.

Since the transesterification is a reversible reaction, therefore, the excess methanol was used to ensure the completion of reaction. This was recovered by distillation method for further use.

3.2 Washing and Neutralization

Due to un-reacted NaOH, PH value of the biodiesel was found to be 9.5. The biodiesel was washed with distilled water repeatedly to remove the

NaOH. The amount of soupy foam went on decreasing with every wash. After fourth wash, the soupy foam was completely absent and crystal clear water was found. At that time the PH value of biodiesel was found to be 6.9 which is very close to that of diesel.

3.3 Testing of CSOME

The properties of CSOME were tested in accordance with the international standards and compared with those of mineral diesel [21] as shown in Table 1.

The density, viscosity, calorific value, and flash point were tested and found within the biodiesel standards of ASTM D 6751.

4. Experimental Setup

The performance tests were conducted with a four stroke, three cylinder, DI, water cooled, naturally aspirated CI engine. The engine was connected to a three phase A.C electric generator of 27 KVA with power factor of 0.9 and of efficiency varying from 80 to 85%. The engine test bed was equipped with fuel measuring, speed control and measuring, load bank, voltage and current measuring system. The exhaust line was connected with a 5 gas exhaust gas analyzer (V402-01). Detailed specifications of the engine are given in Table 2.

Table 2: Engine Specifications

Make	Perkins
Type	AD 3.152
Volumetric efficiency at 25°C	85%
No. of nozzles	3
No. of holes of each nozzle	4
Brake mean effective pressure	7.157 bars
Maximum engine power @ 1500 rpm	27 kW
Bore	91.4 mm
Stroke	127.0 mm
Compression ratio	16.5:1
Injection Timing	17° BTDC

5. Results and Discussion

The experiments were conducted at constant speed of 1500 r.p.m. by varying the load from 3 to 33 kW using B0, B20, B40, B60, B80 and B100 fuel. The engine performance characteristics and exhaust emissions were observed.

5.1 Engine Performance

5.1.1 Fuel Consumption

Rate of fuel consumption (FC) increases with the increase of load, when the engine is fed with diesel and all of its blends with CSOME, as shown in Figure 1(a).

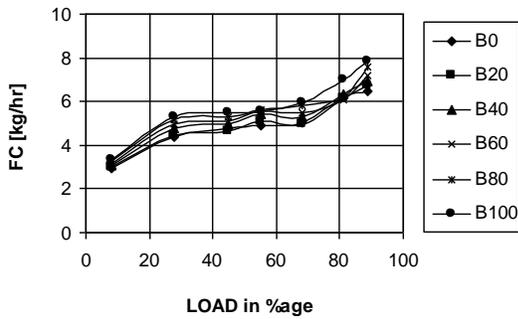


Figure 1(a): Load vs FC

The trends show that there is a very rapid increase in FC up to 27% load, after which it is relatively low up to 70% load. Thus the fuel consumption rate for 27 to 70% load seems to be the best. The rapid increase in FC in the first quarter of the load range is due to high friction and incomplete combustion. After which the combustion becomes better and relatively a smaller amount of fuel per unit load is required. As the load increases above 70%, the combustion becomes incomplete due to lack of time to burn the fuel, which results in higher rate of FC.

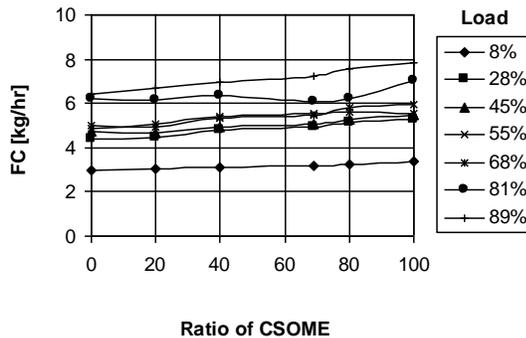


Figure 1(b): Ratio of CSOME vs FC

In Figure 1(b) the rate of FC at different loads is compared using CSOME and its blends with diesel with different ratios. It can be observed that for the same load, the rate of FC goes on increasing with the increase of ratio of CSOME in the blends. The FC increases from 3.4 to 8.0 kg/hr with the increase of load from 8 to 89% for B100 fuel. It is due to the fact that the calorific value of CSOME is lower than that of diesel. It can also be observed that the rate of increase of FC is not very much different up to 70% of CSOME, but it rises sharply for higher ratios. The reason can be the dilemma of combustion of CSOME due its intricate chemistry.

5.1.2 Brake Specific Fuel Consumption

Figure 2(a) shows that brake specific fuel consumption (BSFC) decreases with the increase of load, which is the standard characteristic of the engine.

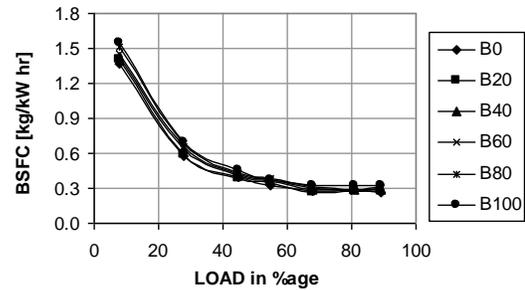


Figure 2(a): Load vs BSFC

It can be observed that the BSFC decreases rapidly in first half of the load. At load more than 50 %, the decrease is relatively small till the 70% load and between 50% to 80% loads BSFC seems to be much reasonable. As the load increases more than 80%, BSFC starts increasing. The optimum working range seems to be between 70 to 80%. Similar types of results have also been obtained by F. K. Forson et al [22].

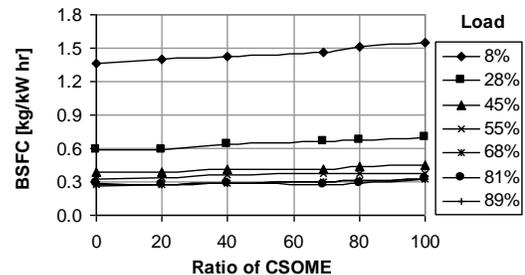


Figure 2(b): Ratio of CSOME vs BSFC

Figure 2(b) shows that BSFC for CSOME and its blends is higher than that of diesel, which is due to lower calorific value of biodiesel. It can also be seen that the optimum point shifts toward the higher load, with the increase of biodiesel contents in the blends of the fuel, which may be due to the fact that the initiation of combustion becomes difficult with the higher ratios of biodiesel. C D. Rakopoulos et al. conducted experiments using biodiesel derived from CSO and other feedstock and obtained the similar results [23].

5.1.3 Brake Thermal efficiency

The trends of brake thermal efficiency (BTE) shown in Figures 3(a) and 3(b), indicate that it increases with the increase of load for diesel and all of its blends up to the optimum range of the load. It increases till 70% load for B0 and till 80% load for B100, while its peak value is between 70 and 80% load for blends of diesel and CSOME in different ratios. It may be due to better combustion and less losses at higher loads.

Although BTE increases with the increase of load for each blend of diesel and CSOME yet the increase in case of higher concentration of biodiesel is relatively lower as compared to the use of diesel alone. P.K. Sahoo et al. have also shown similar trend [6].

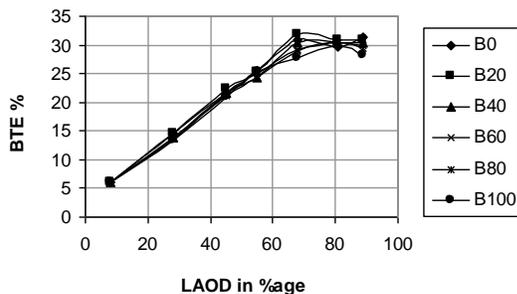


Figure 3(a): Load vs BTE

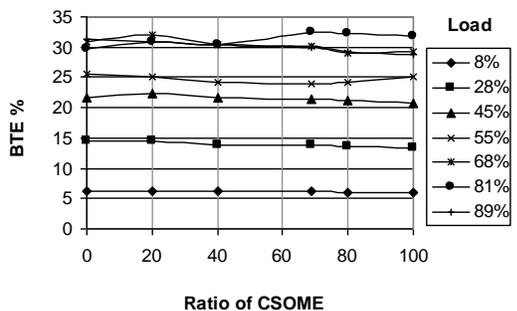


Figure 3(b): Ratio of CSOME vs BTE

As load crosses the optimum limit, BTE starts decreasing for B0 to B100, which is due to the incomplete combustion of fuel and insufficient time available for transfer of heat. This fact has been discussed in emission analysis section in detail. Jehad A. A. et al. also showed similar type of trends [24].

5.2 Emission Analysis

5.2.1 Carbon Dioxide

Carbon dioxide (CO₂) is the major constituent in the exhaust emissions of the engines, which contributes to too many problems like global warming, green house effects etc.

The amount of CO₂ in the emission increases with the increase of load. For B0 it increases from 4.9 kg/hr to 25.4 kg/h, as load increases from 8 to 89%, as shown in Figure 4. This can be understood by the fact that there is an increase in fuel consumption with the increase of load as shown in Figure 1.

Naturally more CO₂ will be produced when more fuel will be burnt to deliver more thermal energy to the engine. This fact has also been endorsed by many other researchers [7, 11, 14].

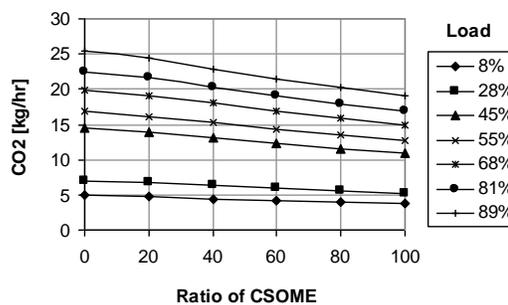


Figure 4: Ratio of CSOME vs CO₂ emission

It can also be seen in Figure 4 that relatively less amount of CO₂ is emitted when engine uses more %age of CSOME. The amount of carbon dioxide reduces from 25.4 kg/hr to 19 kg/hr for 89% load, when the engine is shifted from diesel fuel to CSOME. The reason may be that the biodiesel fuel has less number of carbon atoms and its carbon to hydrogen ratio is lower as compared to diesel. Murat Karabektas et al. have also shown the similar type of results [25].

The amount of CO₂ per kW decreases with the increase of load, which is due to the fact that there is better combustion of fuel for higher load, so less fuel

per kW is consumed resulting in less production of CO₂.

5.2.2 Carbon Monoxide

Carbon monoxide (CO) is a dangerous pollutant gas which is the part of exhaust emissions of engines. It affects the nervous and respiratory systems. Scientists have been putting tremendous effort to design and fabricate the engines emitting reduced amount of CO.

The percentage of CO is already very low in case of compression ignition engines, which can further be reduced with the improvement in engine design, particularly, combustion chamber, ignition timing, and injection system.

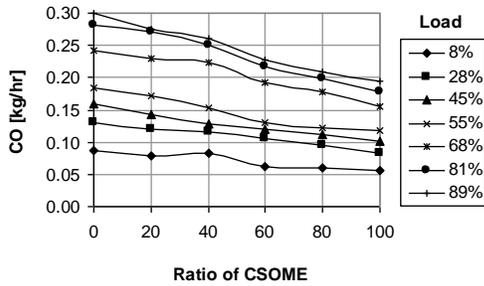


Figure 5: Ratio of CSOME vs CO emission

The amount of CO increases with the increase of load as shown in Figure 5. As the load increases from 8 to 89%, CO increases from 0.09 kg/hr to 0.3 kg/hr for B0. Since data is recorded at constant speed, so the engine inhales almost fixed quantity of air, while amount of fuel goes on increasing for each step of higher load. Thus air fuel ratio decreases, consequently level of CO rises. This fact is exhibited for each blend of fuel.

Biodiesel, particularly CSOME is a God gifted, environmental friendly fuel. When it is used in an engine, there is about 40 % reduction in CO emission as compared to that of diesel emission, as can be seen in Figure 5. The main reason for the reduction in CO is the fact that the biodiesel is an oxygenated fuel. When the fuel decomposes each molecule of CSOME provides two atoms of oxygen. G. Lakshami and his fellow researchers also showed the similar results when they fueled the engine with used cooking oil methyl ester [26].

5.2.3 Oxides of Nitrogen

The oxides of nitrogen (NO_x) emissions are precarious pollutant emissions, which are produced, when the fuel is burnt at high temperature causing

dissociation of N₂, which ultimately leads to the formation of nitric acid. The NO_x is also responsible for weakening the ozone layer.

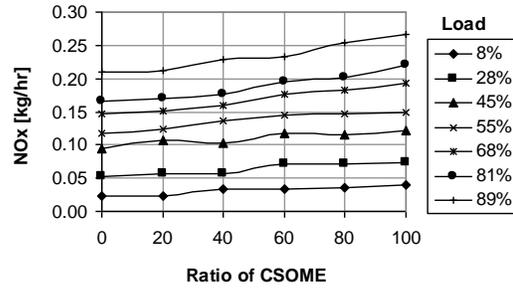


Figure 6: Ratio of CSOME vs NO_x emission

Figure 6 shows that the amount of NO_x is very low for lower load, which increases with increase of load for B0 to B100. The engine temperature increases at higher load, which is responsible for raising the level of NO_x in the exhaust emission.

The NO_x level increases further, with the increase of percentage of CSOME in the blends of fuel. The rise is not very much appreciable up to B20, but it rises sharply for higher ratios of CSOME. The main reason of this phenomenon is the presence of oxygen in the fuel, which facilitates the NO_x formation. Similar results have been shown by C.D. Rakopoulos et al [23]. The raised level can be handled by catalytic conversion, after treatment, and exhaust gas recirculation as proposed by José María López et al [27].

5.2.4 Total Hydrocarbon

The data regarding the unburnt hydrocarbon emission was also recorded at constant speed for different loads, as shown in Figure 7. It can be observed that unburnt total hydrocarbon (THC) increases with the increase of load, for diesel and all of its blends, which may be due to the increase in fuel consumption with the increase of load.

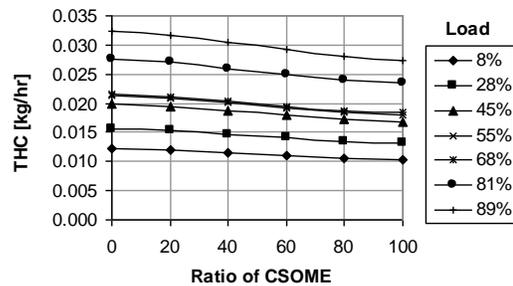


Figure 7: Ratio of CSOME vs THC emission

The THC decreases by using higher ratio of CSOME in the blends at each load. It may be due to the presence of oxygen in the CSOME which leads to efficient combustion. Fortunately, the rate of increase of THC is lower for higher loads using higher concentration of CSOME.

It can be concluded that there is an improvement of combustion efficiency with the increase of load up to optimum range. D.Y. C. Leung et al. also showed the similar results [28]. Almost similar trends are observed for all blends of diesel and CSOME.

6. Conclusions and Recommendations

- CSOME can be used in blended form as an alternative fuel in any compression ignition engine without any modification.
- The FC and BSFC increases and BTE decreases with the increase of ratio of biodiesel in blends of diesel and biodiesel.
- CO, CO₂ and THC emissions are reduced by increasing ratio of biodiesel in the fuel. These pollutant gasses are harmful for environment causing global warming and green house effect and hazardous for respiratory system, nervous system, cardiac system and cause various types of skin diseases. Thus the biodiesel is an environmental friendly fuel.
- The level of NO_x rises in the emissions by increasing the proportion of CSOME in the blend, which can be controlled with catalytic conversion, after treatment, and by some modification in the design of fuel injection system of the engine.
- Since the biodiesel fuel is almost free from sulfur so the exhaust emissions are almost free from SO_x, when the engine is fed with CSOME and its blends
- As the lubricating properties of the biodiesel are better so, the engine life may increase by using biodiesel and frequency of change of lubricating oil would be lower. This aspect is required to be further investigated.
- As the pour point and cloud point of biodiesel are higher than those of diesel, so they may cause problems, particularly in winter season and cold areas. This problem can be handled by adding

additives in the fuel and by adding the heating lines around the fuel tank. More research needs to be done in this regard.

7. Acknowledement

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