INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 2, Issue 1, 2011 pp.179-190

Journal homepage: www.IJEE.IEEFoundation.org

Role of a biodiesel blend in sustaining the energy and environment as a CI engine fuel

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Abstract
In the present work, biodiesel derived from high free fatty acid (FFA) crude rice bran oil, (CRBO) a non-edible vegetable oil was tested as a fuel in a compression ignition engine in blended form to test its suitability and also its ability to create a sustainable environment. A 4.4 kW direct injection stationary diesel engine was used for experimentation. Biodiesel (crude rice bran oil methyl ester) blend was prepared by mixing 20 % crude rice bran oil methyl ester (CRBME) with 80 % diesel on volume basis. An enhanced thermal oxidation was observed for the CRBME blend which oxidizes most of the UBHC into CO and CO_2. As a result of this, UBHC emission and smoke density were reduced by 28 % and 35 % respectively with a marginal increase in CO and NOx emission than diesel. It was also observed that by blending CRBME with diesel, the brake thermal efficiency of the engine decreased only marginally which ensures the suitability of CRBME blend as a CI engine fuel. Experimental results show almost similar performance in CRBME blend when compared to diesel which strengthens its ability to have a sustainable environment. This research work can be extended to improve the thermal oxidation process which may result in further reduction in CO, UBHC and particulate emission than that of the emissions reported in this paper.

Keywords: Biodiesel, Crude rice bran oil, CRBME, Diesel engine, Emission, Vegetable oil.

1. Introduction

In the present energy scenario developing a sustainable energy is a big challenge for the most of the countries in the world. Increasing the consumption of petroleum products will contaminate our environment and hence the sustainable energy search should also be carried out to create a sustainable environment Among all the petroleum products, diesel oil consumption is more and hence there is a need to find an alternative source to achieve the above objectives. Vegetable oil, which is extracted from plant and tree seeds, has an ability to replace diesel oil [1-6]. Vegetable oils have to be utilized as fuels without affecting the availability of edible oil, which may create an economic problem for a country. Several research works were conducted on edible [1, 2, 6] and non-edible [6, 7-10] vegetable oils. Edible oils can not be used as a source of energy since many countries find it difficult to cope up with the demand for domestic use especially in developing nations. Literature indicates that the availability of non-edible vegetable oils is very less for its use as an energy source. In this context, increasing the availability and utilization of non-edible grade vegetable oils will be an optimum solution. In the present investigation, a non-edible vegetable oil with potential availability was chosen and its ability to replace petroleum diesel and sustain the environment was investigated.

Crude rice bran oil (CRBO) is a vegetable oil extracted from rice bran separated from paddy which is a byproduct of rice milling process. Since rice is the staple food for most of the countries, the availability of rice bran for oil extraction is a continuous one. As per the global rice production rate, 7.25 Mt of rice bran oil per year can be extracted which is 1% of the world's diesel consumption [11]. Among the extracted CRBO, less than 10 % only is consumed as an edible oil in some of the Asian countries like India, Japan etc [11]. High free fatty acid (FFA) content of the remaining CRBO has restricted it from being used as edible oil. Hence investigation can be focused to test its ability to replace diesel oil. From the earlier investigations it was inferred that CRBO and its diesel blends have the ability to replace diesel fuel with reduced emissions [11]. Combustion properties of high FFA CRBO blends are similar to that of diesel [12]. Using vegetable oil in a diesel engine in its pure and blended form will create a serious problem in the fuel injection system due to its higher viscosity [13]. To overcome this, the viscosity of vegetable oils is reduced by a process known as transesterification which produces esters of vegetable oil called biodiesel.

In the present investigation biodiesel produced from high FFA CRBO was used in a compression ignition (CI) engine. Biodiesels used in the earlier investigations were derived from various edible and non-edible vegetable oils [1-10] and investigations were not carried out with biodiesel derived from high FFA CRBO. Being a potential non-edible vegetable oil, the present investigation brings out the inherent ability of CRBO as a feed stock for biodiesel production. Earlier research works on biodiesel have indicated that B20 (20% of biodiesel mixed with 80% of diesel on volume basis) will be an optimum fuel blend for a CI engine rather than using any other blend or B100 (100% biodiesel) [14-16]. Blending biodiesel in petroleum diesel is a way to minimize the property differences between petroleum diesel and biodiesel which will still retain some of the benefits of neat biodiesel [17]. B20 is popular because it represents a good balance of cost, emissions, cold weather performance, materials compatibility and solvency. B20 is also the minimum blend level that can be used for EPAct compliance for covered fleets [17]. Hence in the present investigation attention was focused on B20 (obtained by mixing 20% crude rice bran oil methyl ester with 80% diesel on volume basis). Table 1 shows the properties of CRBME blend (20% crude rice bran oil methyl ester with 80% diesel on volume basis) compared with diesel. The performance and emission characteristics of CRBME blend were studied by comparing it with the engine fuelled with diesel oil. The results are also compared with those of other biodiesel blends namely Jatropha methyl ester blend (JTME blend) [18] (20% Jatropha methyl ester with 80% diesel on volume basis) and used cooking oil methyl ester blend (UCME blend) [19] (20% used cooking oil methyl ester with 80% diesel on volume basis).

Table 1. Properties of CRBME blend compared with diesel

Fuel property	Testing method	Diesel	CRBME blend
Viscosity at 40°C (mm^2/sec)	Redwood viscometer	3.522	3.62
Flash point (°C)	ASTM D 92	70	80
Calorific value (kJ/kg)	ASTM D 240-02	43356	42455
Specific gravity	-	0.8	0.845

2. Experimental programme

A stationary engine used for agriculture and small range power generating purpose was used for the investigation. Figure 1 shows the schematic diagram of the experimental set-up and the specifications of the engine are given in Table 2. A swinging field electrical dynamometer was used to apply the load on the engine. This electrical dynamometer with a 5-kVA AC alternator (220V, 1500rpm) was mounted on bearings and on a rigid frame to facilitate the swinging field type loading. The output power was directly obtained by measuring the reaction torque. Reaction force (torque) was measured accurately by a strain gauge type load cell. A water rheostat with an adjustable depth of immersion electrode was provided to dissipate the power generated

Engine testing was carried out at various loads starting from no load to full load. The tests were conducted at a constant rated speed of 1500 rpm. The engine was first run with diesel oil followed by

CRBME blend. Under steady state conditions at each load the fuel flow rate, airflow rate, and the composition of exhaust gases were recorded. Various constituents of exhaust gases like UBHC, CO, NOx, and CO_2 were measured with MRU 1600 exhaust gas analyzer and the smoke intensity was measured with AVL smoke meter.

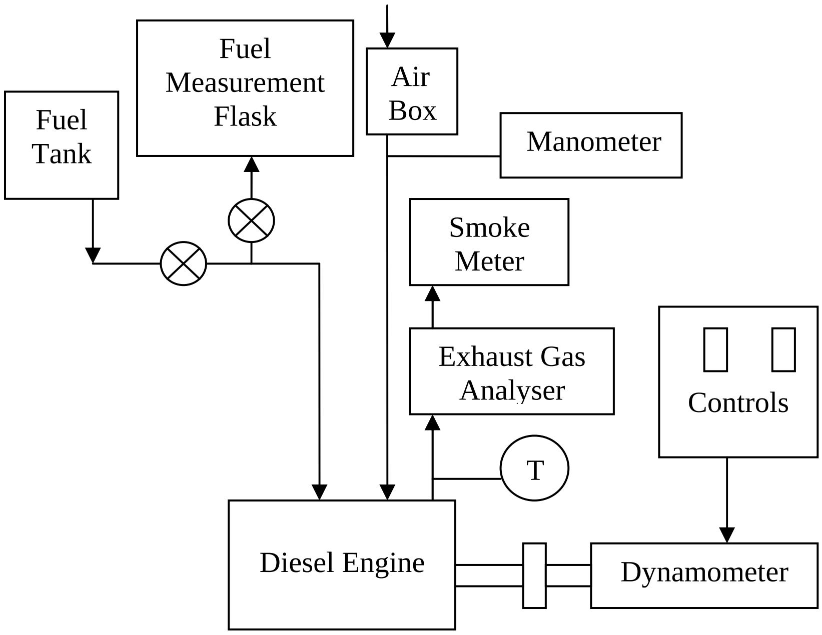

Figure 1. Layout of experimental setup

Table 2. Specifications of engine

Make	Kirloskar
Model	TAF 1
Type	Direct injection, air cooled
Bore × Stroke (mm)	87.5 × 110
Compression ratio	17.5:1
Cubic capacity	0.661 lit
Rated power	4.4 KW
Rated speed	1500 rpm
Start of injection	23.4º bTDC

2.1 Error analysis

The maximum possible errors associated with the measurement of exhaust gas emissions and in the calculation of brake thermal efficiency are presented. Errors were calculated using the method given by Moffat [20]. This method is based on careful specification of the uncertainties in the various experimental measurements.

If an estimated quantity, S depends on independent variables like (x_1, x_2, x_3 …………x_n) then the error in the value of "S" is given by

$$\frac{\partial S}{S} = \left\{ \left(\frac{\partial x_1}{x_1}\right)^2 + \left(\frac{\partial x_2}{x_2}\right)^2 + ... + \left(\frac{\partial x_n}{x_n}\right)^2 \right\}^{\frac{1}{2}} \tag{1}$$

where, $\left(\frac{\partial x_1}{x_1}\right)$, $\left(\frac{\partial x_2}{x_2}\right)$ etc are the errors in the independent variables

∂x_1 = Accuracy of the measuring instrument
x_1 =Minimum Value of the output measured

The error in the brake thermal efficiency (BTE) is given by

$$\left(\frac{\partial BTE}{BTE}\right)=\left(\left(\frac{\partial Torque}{Torque}\right)^2+\left(\frac{\partial rpm}{rpm}\right)^2+\left(\frac{\partial time}{time}\right)^2\right)^{\frac{1}{2}} \tag{2}$$

$$\left(\frac{\partial BTE}{BTE}\right)=\left(\left(\frac{0.021}{7.0}\right)^2+\left(\frac{0.15}{1500}\right)^2+\left(\frac{0.01163}{11.44}\right)^2\right)^{\frac{1}{2}}$$

$$\left(\frac{\partial BTE}{BTE}\right)=\left((0.003)^2+(0.0001)^2+(0.00102)^2\right)^{\frac{1}{2}} = 0.00317 = 0.32\%$$

The exhaust gas emissions were measured using exhaust gas analyzers and smoke meter. As per the specifications of the analyzer the maximum possible error in the measurement of UBHC, CO, NOx and CO_2 emission is $\pm$ 5 %.
To determine the repeatability of the measuring system and to ensure the reliability of the results, the testing procedure was repeated four to five times. By analyzing the experimental results it was found that the exhaust gas measuring system was capable of producing a repeatability of 99.02 % for the measured emission values.

2.1.1 Exhaust gas temperature
Al/Cr K-type thermocouple is used to measure the exhaust gas temperature. Digital temperature indicator displays the temperature measured by thermocouple. The maximum possible error in the case of temperature measurement is calculated from the minimum values of the temperature measured and accuracy of the instrument (Thermocouple with temperature indicator). The errors in the temperature measurement are

$$\left(\frac{\partial T}{T}\right)_{EGT} = \left(\left(\frac{\partial T_{k-type}}{T_{k-type}}\right)^2+\left(\frac{\partial T_{indi}}{T_{indi}}\right)^2\right)^{\frac{1}{2}} \tag{3}$$

$$\left(\frac{\partial T}{T}\right)_{EGT} = \left(\left(\frac{0.48^\circ C}{135^\circ C}\right)^2+\left(\frac{0.468^\circ C}{135^\circ C}\right)^2\right)^{\frac{1}{2}} = \left((0.004)^2+(0.003)^2\right)^{\frac{1}{2}}$$

$$\left(\frac{\partial T}{T}\right)_{EGT} = 0.005 \text{ or } 0.5\%$$

3. Results and discussion
The performance and emission characteristics of the engine fuelled with CRBME blend are discussed and compared to those of the diesel. The emission parameters such as unburned hydrocarbon (UBHC), carbon monoxide (CO), nitrogen oxides (NOx), smoke density and carbon di-oxide (CO_2) are presented at various loads.
Figure 2 compares the brake thermal efficiency of CRBME blend with diesel at different loads. The brake thermal efficiency for CRBME blend is found to be marginally lower on an average by 2.2 % with a standard deviation of 1.17 % when compared to diesel at all loads. Table 3 shows that fatty acids of

CRBO those are the feedstocks for CRBME contains 8-10 %(approx.) of oxygen in its molecular structure. The oxygen present in the CRBME blend initiates the combustion earlier than diesel [21] which may lead to a significant pressure rise before top dead centre (TDC) and may also contribute to increased compression work and heat loss resulting in a decreased brake thermal efficiency. The suitability of CRBME blend as a CI engine fuel was also ensured by only a marginal variation in brake thermal efficiency of the CRBME blend compared to diesel at all the operating conditions. When comparing this result with the earlier works with JTME blend and UCME blend, it can be seen that the decrease in brake thermal efficiency of biodiesel blends is only marginal.

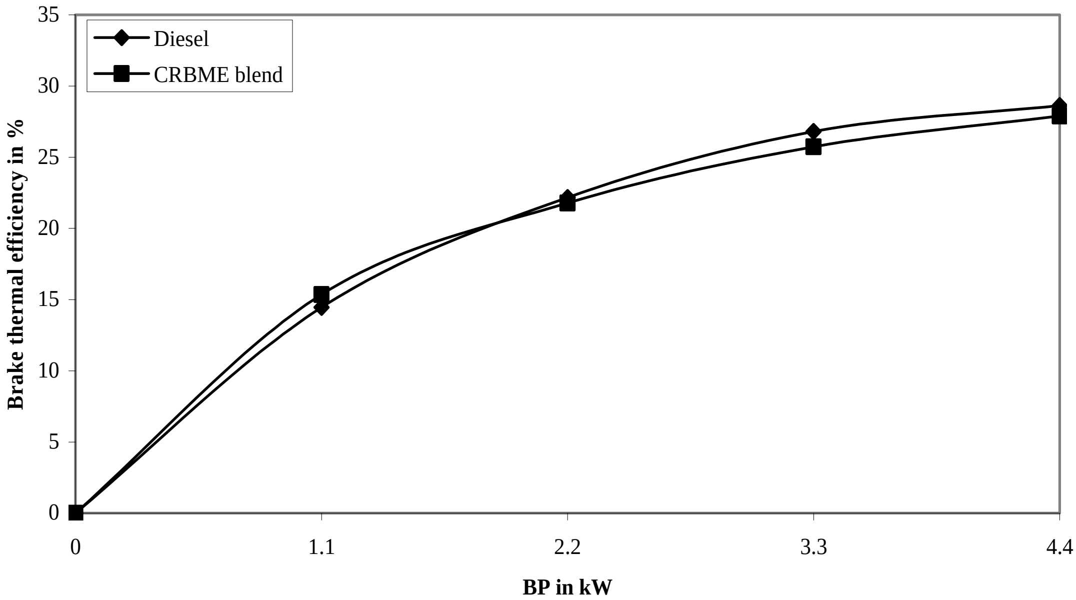

Figure 2. Variation of brake thermal efficiency with load for diesel and CRBME blend

Table 3. Chemical formulae of fatty acids present in the Crude rice bran oil

Name of Fatty acid	Chemical Formulae	Percentage by volume in the Oil
lauric	$C_{12}H_{24}O_2$	0.2
myristic	$C_{14}H_{28}O_2$	0.8
palmitic,	$C_{16}H_{32}O_2$	17.7
arachidic	$C_{20}H_{40}O_2$	0.2
behenic	$C_{22}H_{44}O_2$	0.3
stearic,	$C_{18}H_{36}O_2$	2.2
palmitoleic	$C_{16}H_{30}O_2$	0.23
oleic	$C_{18}H_{34}O_2$	40.6
linoleic,	$C_{18}H_{32}O_2$	35.6
linolenic,	$C_{18}H_{32}O_2$	1.8

Figure 3 shows the variation of exhaust gas temperature with load for diesel and CRBME blend. It can be seen that the exhaust gas temperature increases with increase in load. The exhaust gas temperature is an indication of the combustion chamber temperature. It increases with load due to the increased quantity of fuel burned which liberates more heat at higher loads when compared to lower loads. It can also be observed that CRBME blends show a higher exhaust gas temperature than diesel at all loads which indicates an improved combustion. This may be due to the oxygen present in CRBME [21]. The increase in exhaust gas temperature for CRBME blend is higher than that of JTME and UCME blend. This may be due to the presence of higher percentage of unsaturated fatty acids (80%) [12] when compared with JTME and UCME which may improve combustion process by enhanced oxidation process.

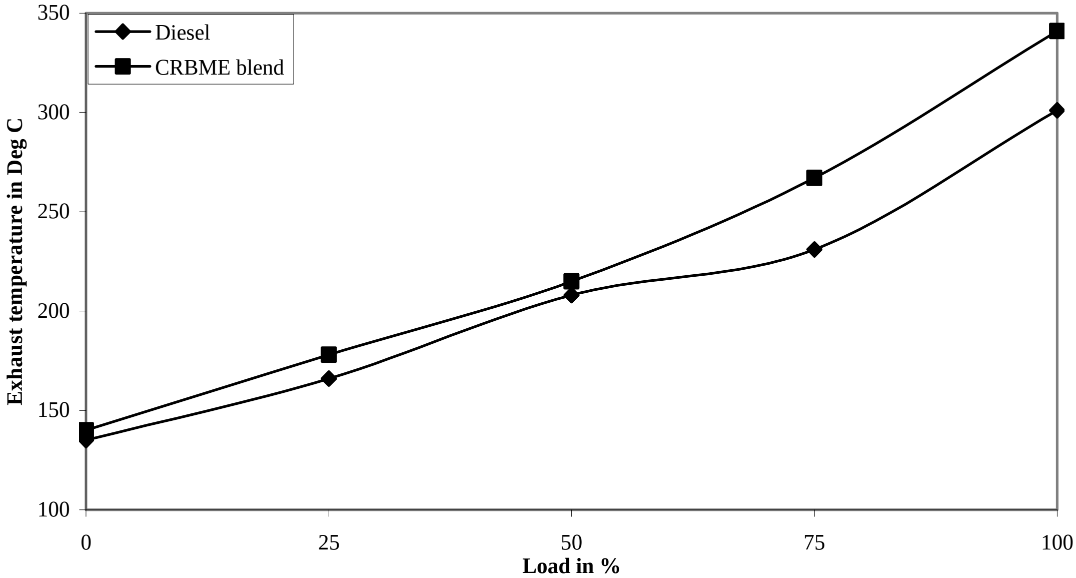

Figure 3. Variation of exhaust gas temperature with load for diesel and CRBME blend

Figure 4 shows the UBHC emission of CRBME blend at various loads compared to that of diesel. It can be observed that the UBHC emission increases as the load on the engine increases. Since the amount of fuel injection is a function of applied load the UBHC emission increases with load. When operating with CRBME blend UBHC emission was reduced on an average of 28 % than that of diesel. As a result of oxygen present in the CRBME blend, the oxygen availability during the combustion process increases which may result in the presence of lean mixture in some parts of the combustion chamber and initiates the thermal oxidation reaction. This reaction may be enhanced by higher combustion temperature at part load operation which may result in a significant reduction in UBHC emission when compared to rated load condition. Even though the temperature is high at the rated load, the presence of rich mixture due to increased quantity of fuel admitted in the combustion chamber increases the formation of UBHC. When compared with other biodiesels, CRBME has higher unsaturated fatty acids in its fatty acid profile which promotes oxidation process in the combustion chamber. This results in higher reduction in the UBHC emission than diesel in the case of CRBME blend when compared to JTME blend and UCME blend

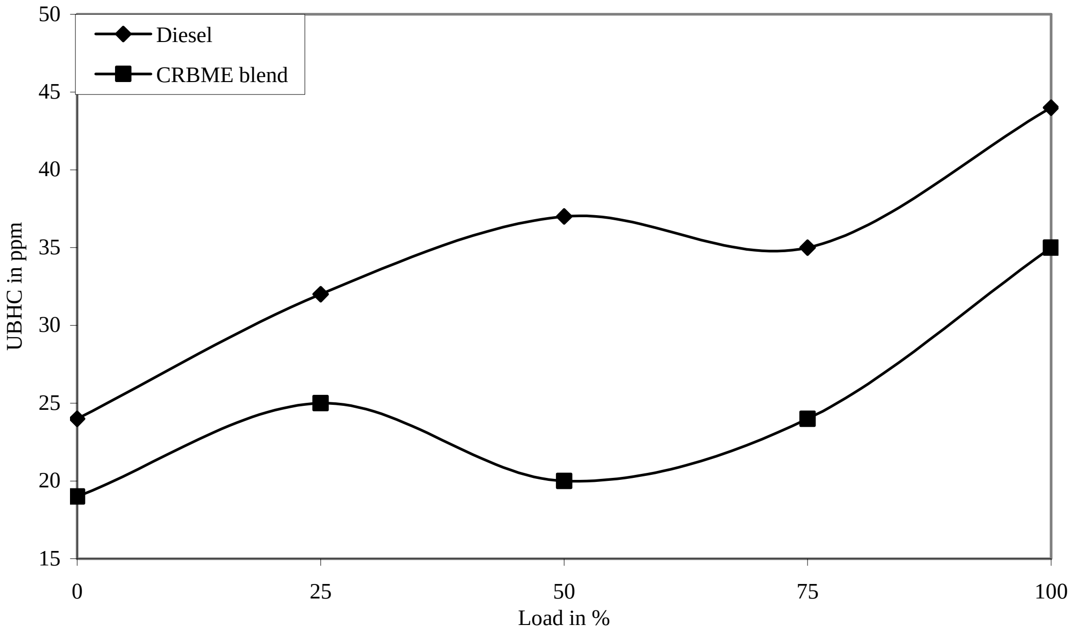

Figure 4. Variation of UBHC emission with load for diesel and CRBME blend

The variation of CO emission with load for CRBME blend and diesel are shown in Figure 5. It can be observed that CO emissions increase with increase in engine load. As the richness of the mixture increases with load it causes an increase in CO emission. Even though the UBHC emission for CRBME blend is lesser than that of diesel, the CO emissions are similar to those of diesel up to 50% of rated load and marginally higher than that of diesel when the engine load is more than the 50% of the rated load. This may be due to the result of thermal oxidation of UBHC at the later stage of combustion process. During this process the unburned hydrocarbons are burned in the presence of oxidizing species to form gaseous CO or CO_2. Oxygen available in the CRBME blend may enhance the oxidation process and result in the formation of gaseous CO. It can be seen that CRBME blend shows a higher CO emission than diesel when compared with JTME blend and UCME blend. As discussed earlier this may be due to the enhanced thermal oxidation as a result of higher unsaturated fatty acids present in CRBME

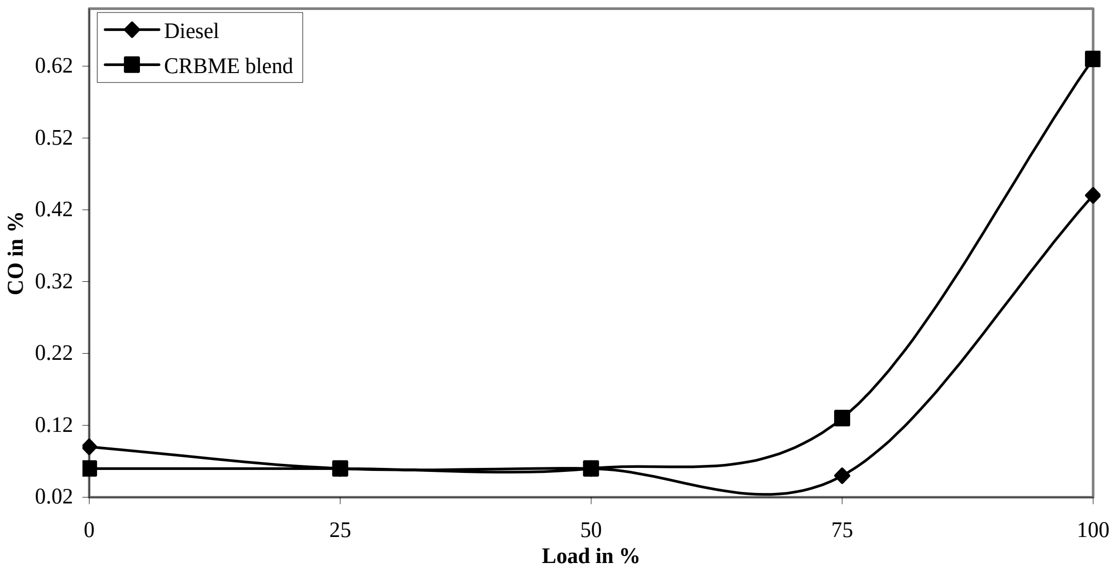

Figure 5. Variation of CO emission with load for diesel and CRBME blend

Figure 6 compares the NOx emission of the CRBME blend with that of diesel at different loads. A marginal difference is observed in the NOx emissions between the CRBME blend and diesel upto 25 % and beyond 75 % of rated load. At other loads CRBME blend exhibits 18 % higher NOx emission than that of diesel. As an oxygenated fuel, CRBME blend improves the combustion process resulting in a higher combustion temperature. This enhances the reaction between free oxygen and nitrogen to form NOx. At no load the mixture leanness is increased by the oxygen present in CRBME which produces a marginal difference in the combustion temperature and NOx emission between CRBME blend and diesel. As the load increases the mixture becomes rich by the increased fuel intake that results in a considerable difference in the incylinder gas temperature and hence in the NOx emission. When compared to other loads the richness of the mixture increases at rated load operation which decreases the combustion temperature and hence the NOx emission. It can also be seen that the NOx emission for CRBME blend is higher than diesel when compared with JTME and UCME blend.

Figure 7 compares the smoke density of CRBME blend with that of diesel. It can be observed that the smoke density increases with load and reaches the maximum at rated load for CRBME blend and diesel. When compared with diesel, the smoke density of CRBME blend is lesser by an average of 35 % with a standard deviation of 28%. It is well known that vegetable oil contains oxygen in its molecular structure [22]. Table 3 shows the chemical formulae of fatty acids of CRBO those are the feedstocks for CRBME contains oxygen in its molecular structure which ensures the presence of oxygen in the CRBME. The oxygen present in the CRBME blend causes an increase in the leanness of the mixture at light-load operation and a decrease in the richness of the mixture at full-load operation. This results in higher reduction in smoke density for CRBME blend at part load operating conditions when compared to full load condition. At no load operation the mixture is lean since the quantity of fuel injected is less. This may lead to form UBHC in some part of the combustion chamber and due to the lower combustion temperature thermal oxidation will be slow which oxidizes some UBHC partially and results in the formation of particulates which increases smoke density. As the load increases the richness of the burning mixture also increases due to the more quantity of fuel injection. Oxygen present in the CRBME blend reduced this richness of the burning mixture and improves the combustion process to get a higher combustion temperature and reduced smoke density than that of diesel. When compared with JTME blend and UCME blend the reduction in smoke density is higher for CRBME blend compared to diesel.

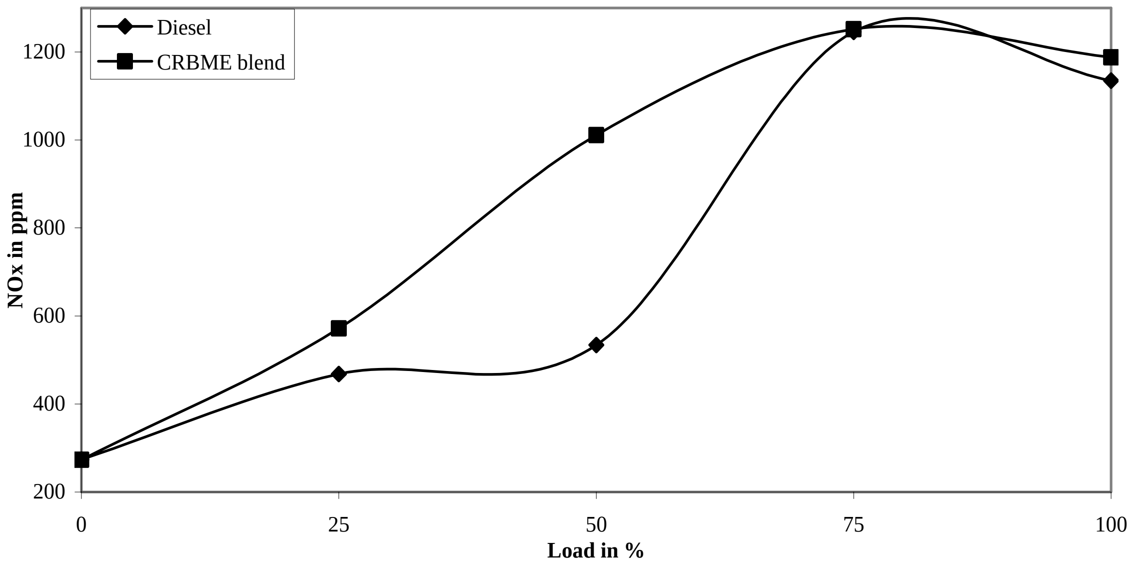

Figure 6. Variation of NOx emission with load for diesel and CRBME blend

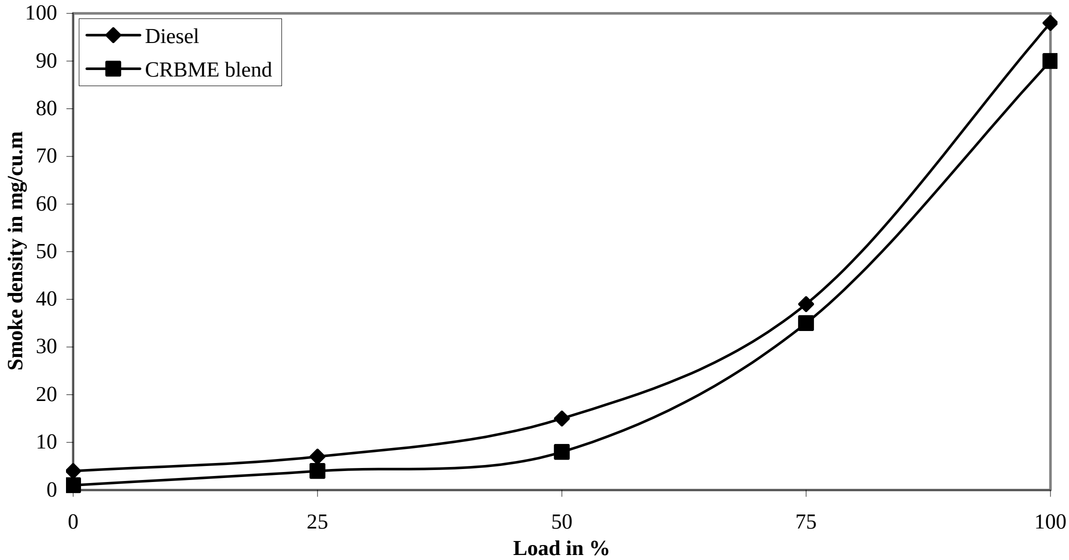

Figure 7. Variation of particulate emission with load for diesel and CRBME blend

Figure 8 compares the CO_2 emission of CRBME blend at different loads with that of diesel. It can be seen that CO_2 emission for CRBME blend and diesel is almost same till the engine reaches 50 % of rated load. At higher loads CO_2 emission of CRBME blend is significantly higher than diesel. At rated load, the oxygen content in the CRBME improves the combustion process, which leads to a complete combustion and hence increased CO_2 emission than that of diesel. As the CO_2 emitted by the CRBME blend will be utilized for the cultivation of plants that would yield seeds the use of CRBME blend will not contribute to global warming.

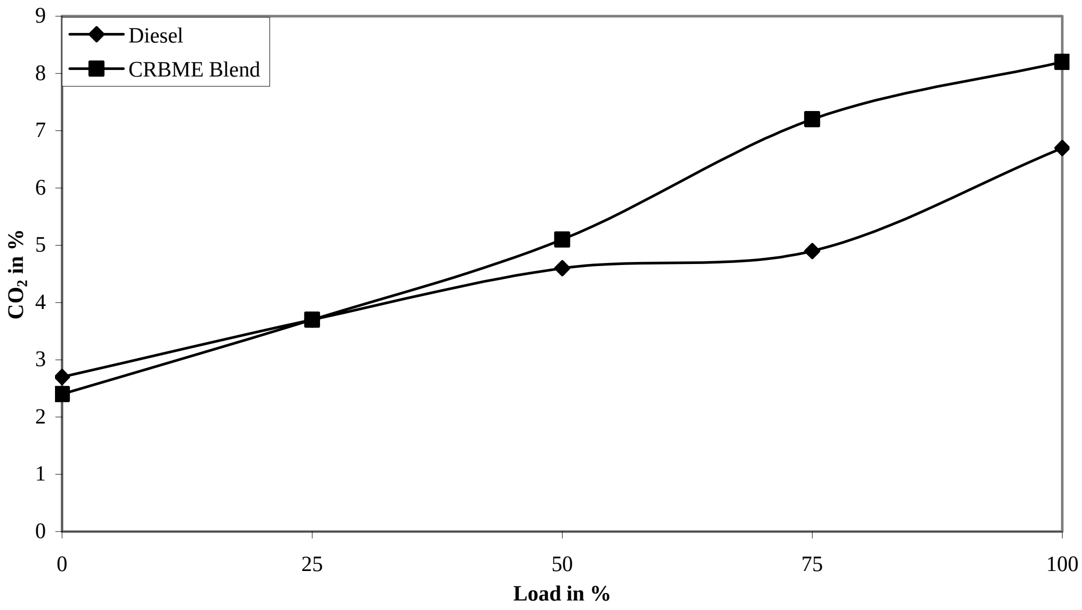

Figure 8. Variation of CO_2 emission with load for diesel and CRBME blend

4. Conclusion
As the previous research works concentrated on using edible vegetable oils in engines, the present investigation brings out with the utilization of biodiesel derived from a non edible vegetable oil namely crude rice bran oil in blend form. As a CI engine fuel, CRBME blend results in an average reduction of 28 % and 35 % of UBHC emission and smoke density respectively with a marginal increase in CO and NOx emission when compared with diesel. Since CRBME blend reduces the environmental pollution without much loss in thermal efficiency when compared with diesel it will be a promising renewable energy source for sustaining the energy. As improved thermal oxidation reaction was observed with CRBME blend when compared to other biodiesel blends tested in the similar kind of engines its role in creating sustainable environment is vital. Further attempts can be made to improve the thermal oxidation process so that the CO formed will be converted into CO_2 to reduce the pollutants substantially.

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