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Full Length Research Paper

Jatropha oil production and an experimental investigation of its use as an alternative fuel in a DI diesel engine

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In this study, a non-edible vegetable oil was produced from *Jatropha* fruits as a substitute fuel for diesel engines and its usability was investigated as pure oil and as a blend with petroleum diesel fuel. A direct injection (DI) diesel engine was tested using diesel, *Jatropha* oil, and blends of *Jatropha* oil and diesel in different proportions. A wide range of engine loads and *Jatropha* oil/diesel ratios of 5/95% (J5), 10/90% (J10), 20/80% (J20), 50/50% (J50), and 80/20% (J80) by volume were considered. The following performance parameters were measured; brake thermal efficiency, brake specific fuel consumption and CO and CO_2 emissions. No significant change in brake thermal efficiency and brake specific fuel consumption was experienced up to J20 ratios. However, higher blends suffered from deterioration in efficiency and fuel consumption about 10 to 25%. At low load operations, CO_2 emission with blends was lower than that of diesel, whereas, at high loads, CO_2 emission became higher with a higher percentage of *Jatropha* oil in the blends. However, CO emission with blends was much higher than that of diesel; the higher the percentage of *Jatropha* oil in the blend, the higher the CO emission.

Key words: Non-edible vegetable oil, *Jatropha* oil, diesel-*Jatropha* oil blends, viscosity and heating, DI diesel engine, performance, emissions.

INTRODUCTION

Using vegetable oil in an internal combustion (IC) engine is not new. A review of literature available in the field of vegetable oil usage has identified many advantages. Vegetable oil is produced domestically which helps to reduce costly petroleum imports, it is biodegradable, non-toxic, contains low aromatics and sulphur and hence, is environment friendly. Personal safety is improved as the flash point is more than 100°C higher than that of diesel. It is usable within the existing petroleum diesel infrastructure with little or no modification to an engine (Chauhan et al., 2010). There are however some challenges. The price of vegetable oil is dependent on the feedstock price, homogeneity, consistency and reliability of supply. Food-fuel conflict of vegetable oils is a burning issue. *Jatropha* oil is non-edible oil and thus, there is no such issue. The high viscosity of vegetable oils may cause engine problems, especially at low operating temperature. Heating the oil or blending with diesel fuel can help solve this problem. Quick (1980), Goering et al. (1981), Bari and Roy (1995) and Sapaun et al. (1996) investigated many vegetable oils in the 80’s and 90’s. Quick (1980) reported that over 30 different vegetable oils have been used to operate compression ignition (CI) engines since the 1900’s. Initial engine performance suggests that these oil-based fuels have great potential as fuel substitutes. During the 1980's, there were many studies that tested the possi-bility of using vegetable oils as a replacement for diesel. Goering et al. (1981) studied the characteristic properties of eleven vegetable oils to determine which oils would be best suited for use as an alternative fuel source. Of the

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eleven oils tested, corn, rapeseed, sesame, cottonseed, and soybean oils had the most favorable fuel properties. Rice bran oil was attempted in a diesel engine by Bari and Roy (1995) in their study. Rice bran oil was blended with kerosene at a ratio of 1:1 (by volume) to reduce the viscosity. Performance results led to the conclusion that rice bran oil can be a very prospective substitute for diesel. Sapaun et al. (1996) reported that, in Malaysia, palm oils can be used as diesel substitutes with promising results. Performance tests indicated that power outputs were almost the same for palm oil, blends of palm oil and diesel, and 100% diesel.

Research on vegetable oil use in diesel engine is still progressing today. A study by Kalam et al. (2003) presented the results of exhaust emissions characteristics of ordinary Malaysian coconut oil blended with conventional diesel oil in a diesel engine. The results showed that the addition of 30% coconut oil with diesel oil produced higher brake power with a net reduction in exhaust emissions. The experiments were undertaken by He and Bao (2005) to test a diesel engine using oil composed of cottonseed oil and conventional diesel fuel. The experimental results showed that a mixing ratio of 30% cottonseed oil and 70% diesel was optimal in ensuring relatively high thermal efficiency of the engine. Research published by Cetin and Yuksel (2007) briefly reviewed the use of hazelnut oil as an alternative fuel in pre-chamber diesel engines, and compared it with diesel. The results showed that the hazelnut oil may be employed in most diesel operating conditions in terms of the performance and emission parameters without any modification or preheating of the fuels. An experimental investigation has been carried out to analyze the performance and emission characteristics of a CI engine fuelled with karanja oil and its blends with petroleum Diesel (K10, K20, K50 and K75) by Agarwall and Rajamanoharan (2009). The effect of temperature on the viscosity of karanja oil has also been investigated. A series of engine tests, with and without preheating have been conducted using each of the above fuel blends for comparative performance evaluation. The results of the experiment in each case were compared with baseline data of diesel fuel. Significant improvements have been observed in the performance parameters of the engine as well as exhaust emissions, when lower blends of karanja oil were used with preheating and also without preheating. Karanja oil blends with diesel (up to K50) without preheating as well as with preheating, can replace diesel for operating the CI engines, giving lower emissions and improved engine performance. Hazar and Aydin (2010) investigated raw rapeseed oil (RRO) and its blends (RRO20 and RRO50) in a DI diesel engine. The effects of fuel preheating to 100℃ on the engine performance and emission characteristics of a CI engine, fueled with rapeseed oil diesel blends were clarified. Results showed that preheating of RRO lowered its viscosity and provided smooth fuel flow. It can also be concluded that preheating of the fuel has some positive effects on engine performance and emissions when operating with vegetable oil. Chauhan et al. (2010) reported that by using a heat exchanger, preheated *Jatropha* oil has the potential to be a substitute fuel for diesel engines. Optimal fuel inlet temperature was found to be 80℃ considering the brake thermal efficiency, brake specific energy consumption and gaseous emissions. A comparable engine performance and emissions are reported by Yilmaz and Morton (2011) using preheated peanut, sunflower and canola oils in two DI diesel engines. No (2011) reviewed seven non-edible vegetable oils including *Jatropha* oil as an alternative fuel for diesel engine. *Jatropha* oil was identified as a leading candidate for the commercialization.

Vegetable oils are considered to be suitable for Thailand due to its agricultural economy, and can help alleviate the problem of under-priced agricultural products. Thailand is blessed with many feedstocks, suitable for vegetable oil production such as palm, *Jatropha*, coconut and sunflower. These crops can be used to produce vegetable oil for usage in the agricultural sector; to decrease the dependence on imported oil and to help stabilize the price of agricultural products. The use of non-edible vegetable oils compared to edible oils is very significant because of the tremendous demand for edible oils as food, making them too expensive to be used as fuel at present. The scientific name of *Jatropha* is *Jatrophs curcas* L. and *Jatropha* oil is one such kind of non-edible vegetable oil. Not only does *Jatropha* have a yield of well over 200 gallons of oil per acre per year, eleven times that of corn (Khan et al., 2009), it also increases the fertility of the land on which it is grown so that it can potentially be used for food crops in subsequent years. *Jatropha* is a perennial which can grow in arid conditions on any kind of ground, and does not suffer in droughts or require irrigation. Therefore, unlike the common biofuel crops of today (corn and sugar); they are very easy to cultivate, even on poor land.

Jatropha is fast growing, begins yielding oil in the second year and continues for forty to fifty years (Yarrapatruni et al., 2009). Optimal yields are obtained from the sixth year. Singh and Padhi (2009) investigated *Jatropha* oil and its methyl ester to find out their suitability for use as petro-diesel. Different properties of *Jatropha* oil were experimentally determined and compared with theoretical equations developed in the study. The study suggested that *Jatropha* oil can be used as a source of triglycerides in manufacture of biodiesel cost-effectively. Pramanik (2003) investigated *Jatropha* oil in a diesel engine. Acceptable thermal efficiencies of the engine were obtained with blends up to J50. Forson et al. (2004) examined the performance of *Jatropha* oil blends in a diesel engine. The most significant conclusion from the study was that the J2.6 produced maximum values of brake power and brake thermal efficiency as well as minimum values of specific fuel consumption. Agarwal and Rajamanoharan (2009) and Hazar and Aydin (2010)

Figure 1. *Jatropha* fruits and seeds.

indicated that the successful use of *Jatropha* oil is a function of engine type, and percentage of *Jatropha* oil in the blends.

This study was therefore undertaken at the Asian Institute of Technology (AIT), Thailand to gather information on the behavior of a diesel engine when operated with *Jatropha* oil and its blend with diesel at different proportions. The objective of this study was to identify the best *Jatropha*-diesel blends, for which the engine performance is similar or better than that of diesel fuel.

MATERIALS AND METHODS

Extraction of *Jatropha* oil

It is reported by Gubitz et al. (1999) that a dry seed of *Jatropha* contains about 55% crude oil by weight. However, the maximum amount of oil that can be extracted from a given sample of the seed depends on the method of extraction and the quality of the feed stock. Two main methods of extracting the oil have been identified. They are the chemical extraction method using solvent extraction with *n*-hexane and the mechanical extraction method using either a manual seed press or an engine driven-expeller. Kpikpi (2002) has reported that solvent extraction with *n*-hexane could produce about 41% yield by weight of oil per kg of the *Jatropha* seed. Foidl and Eder (1997) reported that the dry seed of *Jatropha* would yield about 30 to 38% by expeller. However, in their study in Nicaragua, 30.8% of crude oil by weight was extracted from 12,782 tons of dry weight of *Jatropha* using an engine driven-expeller. Forson et al. (2004) used a ram press and reported that 32 kg of unshelled seeds yielded 6.88 kg of oil representing about 21.5% of crude oil by weight per kg of the unshelled dry weight of the *Jatropha* seed. In the present study, a simple mechanical cracking machine and screw-press available at the AIT, Thailand was used for the oil extraction process. The harvested *Jatropha* fruit was dried for three to four days before cracking. About 150 kg of fruit was fed into the cracking machine. 41.8 kg of seeds was obtained after cracking (Figure 1). *Jatropha* seeds were then pressed by screw-press resulting in a yield of 11.71 kg *Jatropha* oil and 30.09 kg press cake. This means that *Jatropha* oil represented about 28% of crude oil by weight per kg of the *Jatropha* seed. On the assumption that a dry seed of *Jatropha* contains about 55% of oil, the efficiency of the mechanical extraction process used was estimated to be 51%, whereas, a value of more than 90% is reported for extraction with *n*-hexane. This suggests that the mechanical screw-press used, needs some form of improvement.

A cost analysis from cultivating *Jatropha* to obtain the final product of *Jatropha* oil has been performed in this study. The cost of *Jatropha* sprout (tree), land preparation, maintenance and labor was considered. *Jatropha* sprout costs 30 to 60% of the total cost. *Jatropha* sprout price can vary from 3 to 10 baht (1 US$ = 31 baht) per tree. *Jatropha* oil production cost was 14.67 baht/l when the sprout price was 3 baht/tree and increased to 24.64 baht/l when the sprout price increased to 10 baht/tree. The petro-diesel price selected by Thai Government Ministry of Energy was then 30 baht/l. *Jatropha* oil price was therefore lower than that of diesel for all sprout prices.

Chemical and physical properties

The chemical and physical properties of *Jatropha* oil and diesel were tested according to ASTM Standard (D975/D6751) by PTT Research and Technology Institute and PTT Public Company Limited.

RESULTS AND DISCUSSION

The results of chemical and physical properties of *Jatropha* oil and diesel are shown in Table 1. The results show that the higher heating value of *Jatropha* oil is about 85% to that of diesel and the pour point is very similar. However, the flash point and the kinematic viscosity of *Jatropha* oil are several times higher than diesel. The lower heating value of *Jatropha* oil is an indication that a higher oil consumption than that of diesel is needed for similar power output. Similar low pour points of diesel and *Jatropha* oil suggest that *Jatropha* oil can be used at low temperatures just like diesel. Due to a higher flash point,

Jatropha oil is safer for storing and transporting when compared to diesel. Kumar et al. (2003) reported that the cetane number of *Jatropha* oil is about 15% lower than that of diesel, therefore, higher *Jatropha* oil blends or pure *Jatropha* oil combustion might be less efficient. *Jatropha* oil's viscosity is about ten times that of diesel, leading to problems of fuel atomization and proper combustion. Therefore, *Jatropha* oil's viscosity reduction will be described in the next sections.

Reducing *Jatropha* oil's viscosity

High viscosity is a major problem when using vegetable oil as an alternative fuel for diesel engines. In the present

Table 1. Properties of *Jatropha* oil and diesel.

Properties	*Jatropha* oil	Diesel
Higher heating value (MJ/kg)	38.36	45.0
Lower heating value (MJ/kg)	37.65	42.5
Flash point (ºC)	> 180	64
Pour point (ºC)	-3	-2
*Cetane number	40-45	45-55
Sulphur content (% wt.)	0.0002	0.033
Density (kg/m^3, at 15°C)	916.87	845
Kinematic viscosity (cSt, at 40ºC)	39.07	3.137

*Kumar et al. (2003).

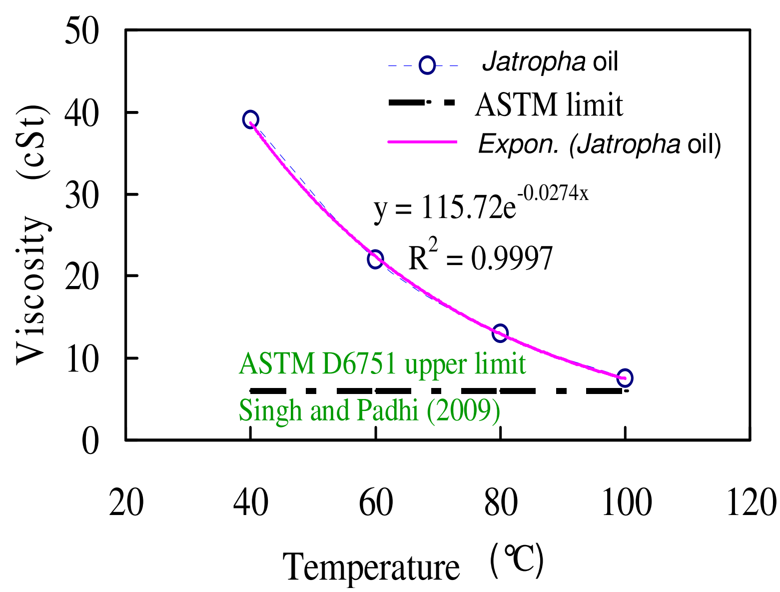

Figure 2. Relationship between viscosity and temperature of *Jatropha* oil.

investigations, viscosity was reduced by heating and blending the oil with diesel fuel. The viscosity of *Jatropha* oil was measured by a calibrated glass capillary viscometer using ASTM D445 method at different temperatures in the range of 40 to 100°C. The results are shown in Figure 2. The viscosity of *Jatropha* oil decreased remarkably with increasing temperature and it became close to ASTM limits (ASTM D6751) for viscosity of biofuels when the temperature 100°C or more. Figure 2 also shows a good relationship between viscosity and temperature presented by an exponential equation, $y = 115.72\ e^{-0.0274x}$, where y is kinematic viscosity and x temperature.

Agarwal (1998) and Sinha and Misra (1997) reported that dilution or blending of vegetable oil with other fuels like alcohol or diesel fuel would bring the viscosity close to specification range. Therefore, *Jatropha* oil was blended with diesel in varying proportions (J5, J10, J20, J50 and J80) with the intention of reducing its viscosity close to that of diesel fuel. The viscosity of various blends of *Jatropha* oil and diesel was also evaluated (Figure 3). The viscosity of *Jatropha* oil decreased after blending. The viscosity of J5 and J10 was within the ASTM limit. The viscosity reduction of J20 is about 85%, and very close to ASTM limit. For the three *Jatropha* oil blends (J5, J10 and J20), corresponding viscosity was found to be 3.94, 4.63, and 6.5 cSt at 40°C, respectively.

Engine test procedure

Constant speed engine tests were carried out using *Jatropha*-diesel blends, pure *Jatropha* oil and diesel. The performance of the engine was evaluated in terms of brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature. The make of the engine

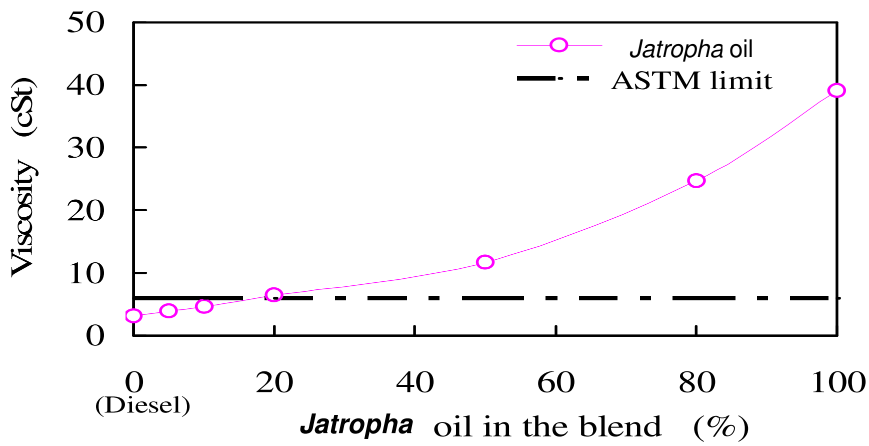

Figure 3. Effect of blending diesel on the viscosity of *Jatropha* blends.

Table 2. Engine specifications.

Specifications	Descriptions
Engine type	4-stroke DI diesel engine
Number of cylinders	Three
Bore × Stroke	91.4 × 127 mm
Swept volume	2500 cc
Compression ratio	18.5:1
Rated power	36.6 kW at 2250 rpm
Start of injection	20° BTDC
Injection pressure	20 MPa

used in this study was Perkins. Engine specifications are given in Table 2. The engine speed was kept constant at maximum brake torque (MBT) speed of 1500 rpm. Fresh lubricating oil was filled in the oil sump before starting the experiments. Loads were measured by electric dynamometer. Seven load conditions (from no load to full load) are reported. The fuel supply system was modified by adding an additional three-way, hand operated, two-positional directional control valve which allowed rapid switching between the diesel oil used as a standard and the test fuels. The engine was started with diesel and once the engine warmed up, it was switched over to *Jatropha* oil or blends. After concluding the tests with *Jatropha* oil or blends, the engine was again switched back to diesel, before stopping the engine until the *Jatropha* oil or blends was purged from the fuel line, injection pump and injector in order to prevent deposits and cold starting problems. Stop watch and fuel level indicator are used to measure the fuel consumption rate. An orifice meter-inclined manometer arrangement was used to measure the intake air flow rate. Thermocouples with temperature indicator were installed to measure intake air and exhaust gas temperatures. A gas analyzer was used to measure the CO_2 and CO emissions in exhaust gases.

At every test point, data samples were taken at least thrice, but a single point (average of data) is used to present the results graphically. Similar conditions were maintained for all tests to allow direct comparison of the results. The standard deviations of important performance and emission parameters are approximately: 0.25% for brake thermal efficiency, 0.015 kg/kWh for brake specific fuel consumption, 0.0025% for CO and 0.2% for CO_2.

Engine performance and emissions

The variation of brake thermal efficiency of the engine with various blends and *Jatropha* oil is shown in Figure 4 and compared with the brake thermal efficiency obtained with diesel. The brake power is increased from 0 kW for no load up to about 16.75 kW for full load with different fuels. The maximum thermal efficiency obtained with diesel fuel is slightly higher than 30%. J5 showed slightly higher thermal efficiency than diesel. J10 and J20 showed similar thermal efficiency, but J50 and higher blends showed 3 to 5% less thermal efficiency than

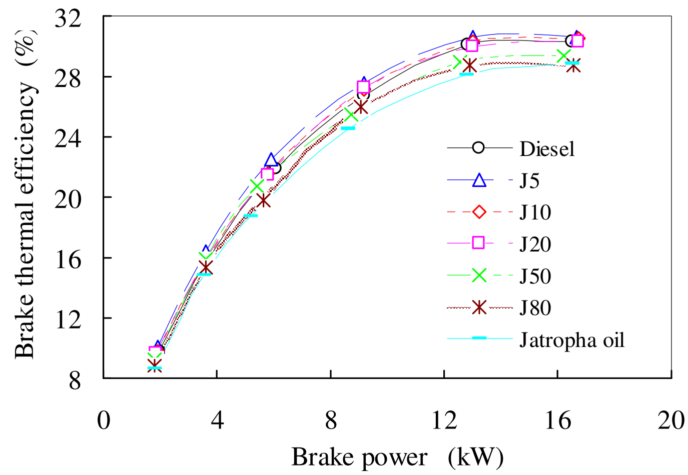

Figure 4. Brake thermal efficiency of the engine with various fuels.

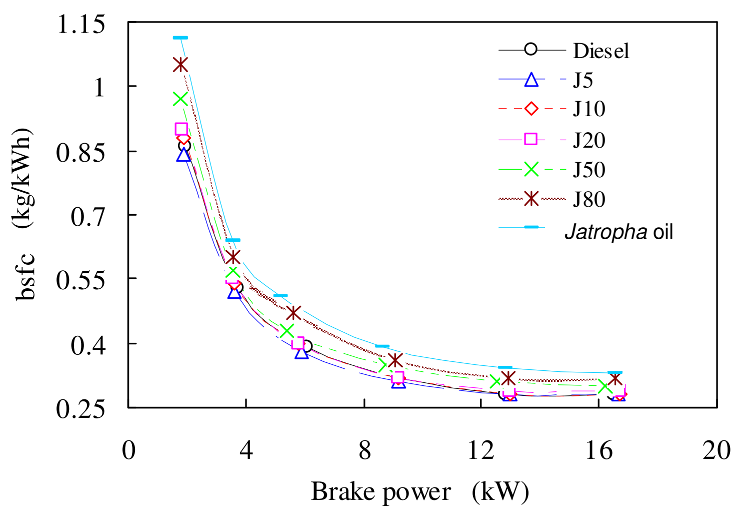

Figure 5. Brake specific fuel consumption of the engine with various fuels.

diesel fuel. The observation is that the higher the *Jatropha* oil in the blends, the higher the reduction in the thermal efficiency. The reasons might be explained as follows. Due to very high viscosity and low volatility of *Jatropha* oil, higher *Jatropha* oil blends suffer from worse atomization and vaporization followed by inadequate mixing with air. The consequence is inefficient combustion. This suggests that high fuel injection pressure and improved volatility might be helpful for better combustion with higher thermal efficiency for higher *Jatropha* blends.

Figure 5 shows the variation of brake specific fuel consumption (bsfc) of the engine with various fuels. The bsfc is decreased from 0.87 kg/kWh at low load to 0.28 kg/kWh at full load for diesel fuel. The best bsfc obtained with diesel fuel is 0.28 kg/kWh at full load operation. Better bsfc is obtained for the J5 than diesel. This blend shows about 3% less bsfc in average than diesel fuel. Diesel and J5 have almost the same heating value. However, J5 has some oxygen present, which might have favored better combustion than the diesel only operation. The deterioration in bsfc up to J20 is 1.5 to 3.4%. J50, J80, and pure *Jatropha* oil show average bsfc deterioration of about 10, 15 and 25%, respectively. In the case of pure *Jatropha* oil, deterioration in bsfc at no or low load (up to about 30% load) condition is about 30%, whereas the load above that, the bsfc deterioration decreased to about 20%. A similar trend (the lower the loads, the higher the deterioration in the bsfc) is found for J80 and J50 blends. At low load conditions, the cylinder temperatures are low. Due to poor volatility of pure *Jatropha* oil, low cylinder temperature at low load conditions might not favor proper combustion. It seems that blending of *Jatropha* oil with kerosene instead of diesel, which was investigated by one author of this paper using

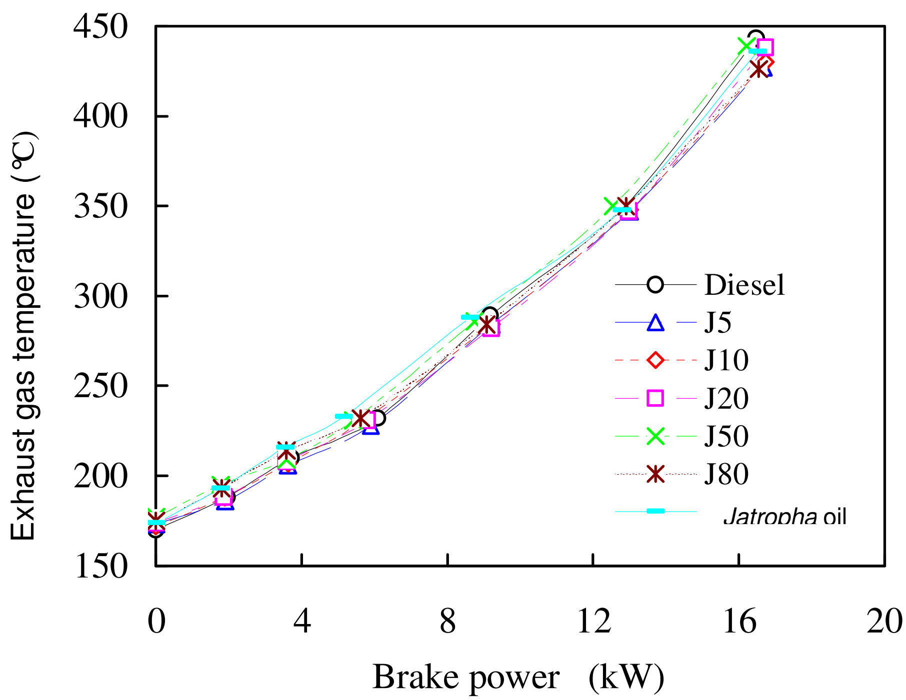

Figure 6. Exhaust gas temperatures with various fuels.

rice bran oil (Bari and Roy, 1995), might have better volatility that could improve combustion and bsfc. Furthermore, a higher amount of *Jatropha* oil can be blended without deterioration in efficiency and bsfc. Lower heating value (which was used to calculate engine efficiency) of *Jatropha* oil (37.65 MJ/kg) is about 11% less than diesel (42.5 MJ/kg) in terms of mass basis. When it is converted in volume basis (for example energy content per liter), *Jatropha* oil has only about 4% less energy content than diesel. This suggests that if specific fuel consumption is measured by volumetric basis (l/kWh), which is logical for liquid fuels as they are traded as volume basis, there will be no reduction in fuel consumption up to J20 as compared to diesel.

Figure 6 shows the variation of exhaust gas temperature with load in the range of 0 to 16.75 kW for diesel, pure *Jatropha* oil and various blends. The results show that the exhaust gas temperature increased with increase in brake power in all cases. The highest value of exhaust gas temperature of 443℃ was observed with diesel, whereas, the corresponding value with *Jatropha* oil was found to be 436℃. There was no significant difference in exhaust gas temperature among various blends and pure diesel and *Jatropha* oil. The average exhaust gas temperature with different blends is more than 250℃. This high temperature exhaust gas can be used to preheat the *Jatropha* oil or blends for improved performance.

Figure 7 shows CO_2 emissions at various engine loads for different fuels. The increase in CO_2 emissions at lower load conditions is not sharp. However, at engine loads above 50% there is a steep increase in CO_2 emissions for all fuels. At lower load operations, *Jatropha* oil blends, especially higher ones, produced less CO_2 than diesel, indicating a less efficient combustion. This is very consistent to that described in Figure 5, that is, low cylinder temperature at low load conditions does not favor proper combustion of *Jatropha* oil and higher blends. At higher load conditions (80% or higher), J50 and *Jatropha* oil produced about 20% higher CO_2 than diesel. This is thought to be partially due to improved efficiency at higher load conditions and mostly due to much higher fuel consumption of *Jatropha* oil and higher blends than diesel at this condition.

Figure 8 shows CO emissions at various engine loads for different fuels. The general trend is that CO gradually decreased up to about 80% load and then increased sharply at full load operation for all fuels. J5 produced about 50% more CO than diesel throughout the operation. J10 and higher blends produced about double the CO when compared to diesel. Less CO was expected with *Jatropha* oil and blends than diesel due to *Jatropha* oil's inherent O_2 content, which might have helped combustion (especially at high loads), where diesel operation was starved for oxygen. Excess air factor (λ) is measured to determine if the engine is starved for oxygen at high load operations.

Figure 9 shows excess air factor of different fuels tested at various engine loads. The excess air factor is decreased from 5.75 at no load to 1.75 at full load for diesel fuel. To calculate excess air factor, it is necessary to know the stoichiometric air/fuel (A/F) ratio of different

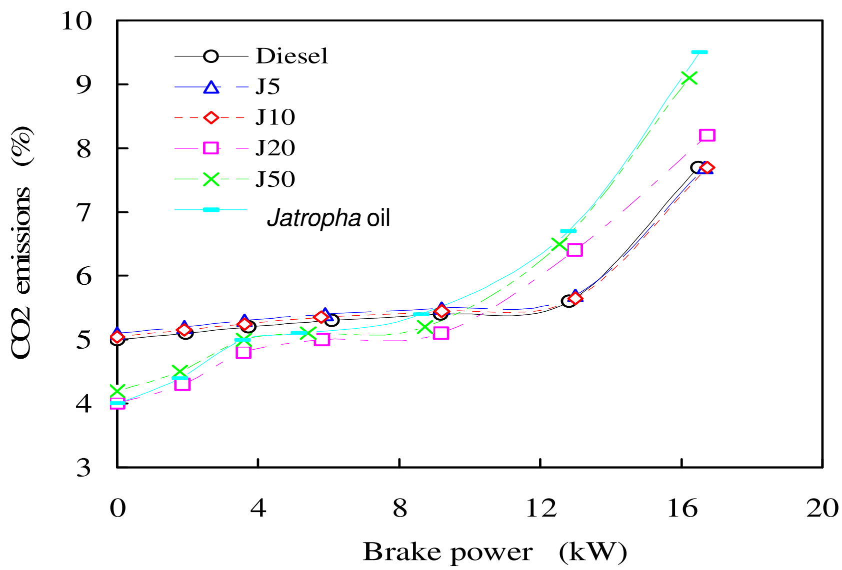

Figure 7. CO_2 emissions with various fuels.

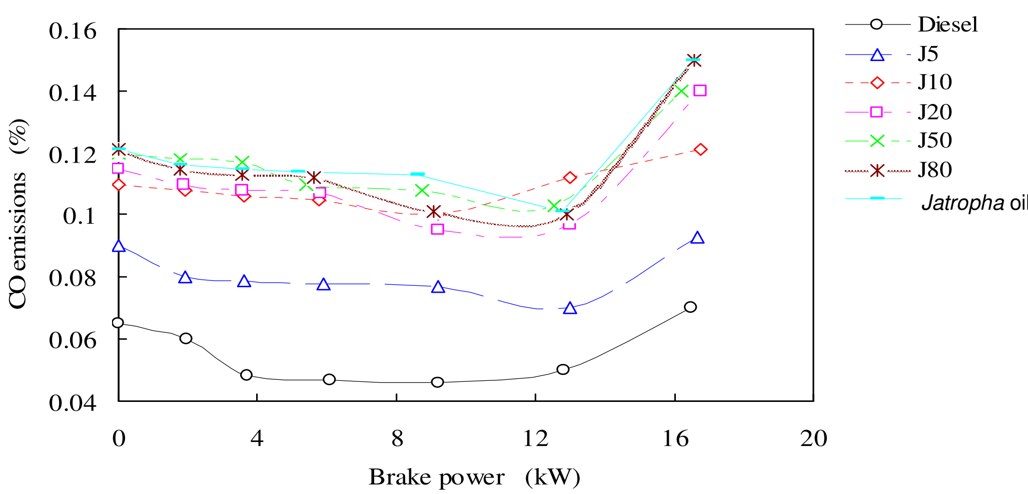

Figure 8. CO emissions with various fuels.

fuels. The conventional value of stoichiometric A/F ratio for diesel is taken as 14.7. The stoichiometric A/F ratio of *Jatropha* oil is calculated as 12.1 based on the ultimate analysis of *Jatropha* oil presented by Agarwal and Agarwal. (2007). The lowest excess air factor obtained with diesel fuel is 1.75 at full load operation. This means that there is still 75% excess air. Excess air factor of *Jatropha* blends is higher than diesel at almost all load conditions. At full load operation with *Jatropha* oil and blends, there is about 80% excess air. The amount of excess air with *Jatropha* oil and blends is higher than diesel, but much higher CO is produced with those fuels. This is possibly a result of poor spray atomization and improper local air/fuel mixture formation with *Jatropha* oil and blends.

Optimum proportion of *Jatropha* oil in the blends

Root mean squared error (RMSE) was used for comparative assessment of engine performance between diesel and *Jatropha* oil blends. The formula used is given as:

$$RMSE = \sqrt{1/n\sum_{i=1}^{n}(D_i-J_i)^2}$$

Where: D_i is the performance parameters of diesel for i^{th} value of load, J_i is the performance parameters of

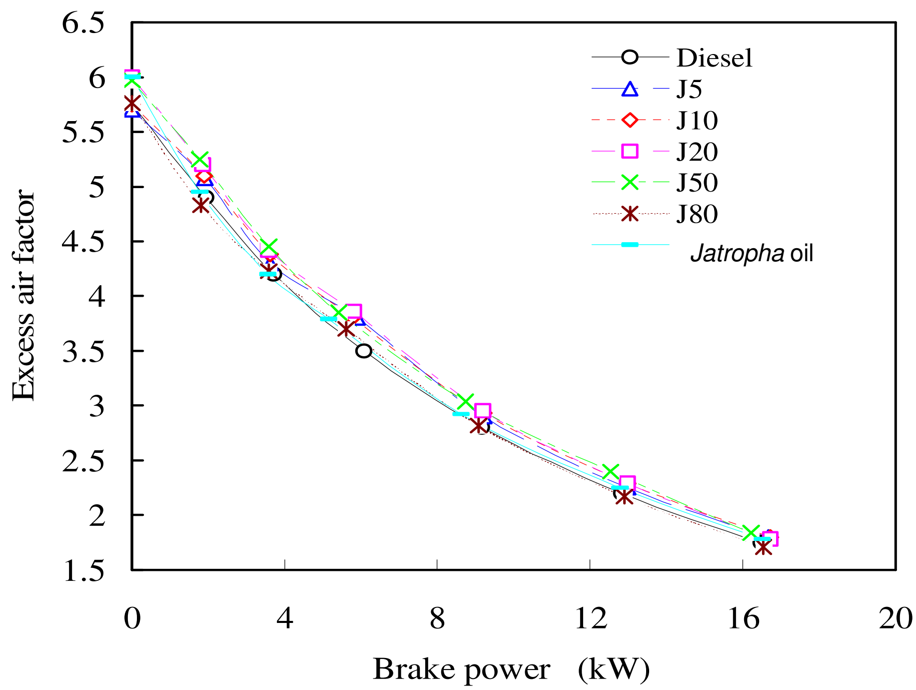

Figure 9. Excess air factor with various fuels.

Table 3. Root mean squared errors between diesel and various *Jatropha* oil blends.

	J5	J10	J20	J50	J80	*Jatropha* oil
Root mean squared error (in brake thermal efficiency, %)	0.0001	0.0001	0.0001	0.0002	0.0004	0.0006
Root mean squared error (in bsfc, kg/kWh)	0.0012	0.0012	0.0015	0.0085	0.0111	0.0144

Jatropha oil and blends for the corresponding i^{th} value of load, n is the number of loading, here, 6.

Table 3 shows the RMSE between diesel and different *Jatropha* oil blends. The results show that J5 to J20 have the lowest value of RMSE of brake thermal efficiency (0.0001), while the lowest value of RMSE of brake specific fuel consumption is 0.00012 for J5 and J10. This means that *Jatropha* oil blends up to 10% have an engine performance (both efficiency and fuel consumption) very close to that of diesel fuel. In addition, the ASTM limit for viscosity should be taken into consideration. J10 also satisfies the ASTM standard of viscosity. In conclusion, the results obtained show that blends up to J10, are optimum for diesel substitute without any engine modify-cation. This is much better than that reported by Forson et al. (2004), where J2.6 was recommended. Forson et al. did not test *Jatropha* oil blends in the range of 2.6 and 20%. J5 showed the best results (even better than diesel) in this study. However, up to J20, the engine performance is comparable with diesel operation. Although, results up to J20 are promising, durability tests are required for long term usage of these oil blends in the engine.

Yilmaz and Morton (2011), No (2011) and Haldar et al. (2009) reported the results of engine performance and emissions for peanut, sunflower and canola as edible oils and *Jatropha*, karanja, mahua, linseed, rubber seed, cottonseed, neemoils and Putranjiva as inedible oils. They showed that the performance and most of the emissions (except NOx) of 10 to 20% oil blends are very similar or better than that of petro-diesel. This study shows similar and comparable results up to J20, with J5 shown to perform better than petro-diesel.

CONCLUSIONS AND RECOMMENDATIONS

Jatropha oil production from *Jatropha* fruits, its fuel characterization, temperature-viscosity relations and an experimental investigation were conducted to explore the performance of *Jatropha* oil and blends as a diesel substitute. The results obtained suggest the following conclusions:

1. A good relationship between viscosity and temperature

of *Jatropha* oil was established. It was found that heating the *Jatropha* oil to about 100℃ is adequate to reduce the viscosity to within close range of the ASTM limits of viscosity for biofuels. Viscosity of *Jatropha* blends (up to J20) was also found to be close to the ASTM limit.

2. From the experimental results obtained, *Jatropha* oil is found to be a promising alternative fuel for CI engines. It can be used for blending up to J20 without any reduction in thermal efficiency. J5 showed better thermal efficiency and bsfc than diesel. From the analysis of optimum proportion of *Jatropha* blend, up to J10 showed very good performance.

3. Emissions of CO_2 with *Jatropha* oil blends up to moderate loads are lower than that with diesel fuel. When the load is 50% or higher, J50 and higher blends produced about 20% higher CO_2 than diesel.

4. Emissions of CO with *Jatropha* oil and blends are much higher than diesel at all loading conditions, although the engine always ran leaner with *Jatropha* oil and blends than diesel. This suggests improving the local air/fuel mixture when operated by *Jatropha* oil and blends.

Two recommendations are proposed for further work which will also include the study of NOx and PM emissions:

1. Engine test with pure *Jatropha* oil at higher fuel injection pressures (up to 100 MPa or more) with a smaller nozzle hole diameter (as small as 0.1 mm) to improve atomization. This also improves the in homogeneity of local air fuel mixture.

2. Dilution (blending) of *Jatropha* oil with kerosene instead of diesel. This would improve volatility. Moreover, higher percentage of *Jatropha* oil blending is possible within the ASTM limit of viscosity due to the lower viscosity of kerosene than diesel.

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