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Scope and limitations of utilization of non-edible straight vegetable oils (SVO's) as a substitute fuel for diesel engines: an experimental study

Avinash Kumar Agarwal
Associate Professor, Department of Mechanical Engineering,
Indian Institute of Technology Kanpur, Kanpur – 208016, India

Presenting author's E-mail: akag@iitk.ac.in

Abstract
Straight vegetable oils (SVO's) have been evaluated as substitutes for diesel fuels with the depletion in petroleum resources and concern of CO_2 caused global warming. However, several operational and durability problems of using straight vegetable oils in diesel engines are reported in the literature, caused by their higher viscosity and low volatility compared to mineral diesel. This viscosity can be brought in acceptable range by transesterification, blending of oil with diesel and heating the oil by utilizing exhaust heat. Reduction in viscosity by blending or preheating by exhaust gas has cost advantage compared to viscosity reduction by transesterification.
The use of straight vegetable oils as a fuel substitute for diesel engines for rural sector is currently being debated upon in the country. This paper presents the technical feasibility of using straight vegetable oils (Jatropha oil), into a constant speed direct injection compression ignition engine. Vegetable oils have very high viscosity, which make their direct usability in engines questionable. In this investigation, SVO's were preheated by using waste heat from engine exhaust, in order to reduce their viscosity. The effect of using these oils on typical engine problems such as injector coking, piston ring sticking, lube oil dilution etc. was investigated in detail. Long-term endurance test (For a duration of 512 hours) of SVO fuelled engine vis-à-vis mineral diesel fuelled engine was executed and the results are compared.

Introduction
Diesel engines are the most efficient engines commonly available today. Diesel engines have provided power units for transportation systems (passenger cars, buses etc.), goods transportation systems (trucks etc.), ships, railway locomotives, non-road equipment used for farming and construction, and in almost every type of industry due to their economy of operation and durability. They are important part of the public and private transportation sector and their use will continue and grow further in future. The diesel engine does all this in a package that is robust and durable, with lower fuel consumption than any other prime mover. However, diesel engines are one of the largest contributors to environmental pollution problems worldwide. Diesel emissions contribute to development of cancer; cardiovascular and respiratory health effects; pollution of air, water, and soil; reduction in visibility; and global climate change.
Compared to the rest of the world, India's demand for diesel fuels is roughly six times that of gasoline. According to an estimate, India consumed about 40.34 million tons of mineral diesel in 2000-2001, which was 43.2% of its total consumption of petroleum products, and two-thirds of this demand was met by import of diesel costing about Rs. 200 billion. With an expected growth rate of diesel consumption in excess of 14% per annum, shrinking crude oil reserves and limited refining capacity, India will continue to heavily dependent on import of crude petroleum and petroleum products. From the point of view of protecting the global environment and concerns for long-term energy security, it becomes necessary to develop alternative fuels with properties comparable to conventional fuels.
Alternative Fuels: Alternative fuels should be easily available, environment friendly and techno-economically competitive. Successful alternative fuel should fulfill environmental and energy security needs without sacrificing engine operating performance. Renewable

resources offer the opportunity to tap local and renewable resources and reduce dependence on imported energy resources.

For the developing countries of the world, fuels of bio-origin provide a feasible solution to the twin crises of fossil fuel depletion and environmental degradation. It is not a new idea to use vegetable oils as fuel for diesel engines as fuel. When Rudolf diesel invented diesel engine, he demonstrated it at the 1900 world exhibition in Paris, employing peanut oil and said, “The use of vegetable oils for engine fuels may seem insignificant today, but such oils may become in course of time as important as petroleum and the coal tar products of present times”[1]. With the advent of cheap petroleum, appropriate crude oil fractions were refined to serve as fuel thus diesel fuels and diesel engines started evolving together. In the 1930’s and 1940’s, vegetable oils were used as diesel engine fuels from time to time during emergencies. There has been renewed interest in biofuels after the oil-shocks of 1970’s, 1991 gulf war and oil crisis of 2007-08. Now bio-fuels are getting a renewed attention because of global stress on reduction of green house gases and Clean Development Mechanism (CDM). In addition, the use of vegetable oils as fuel is less polluting than petroleum fuels [2].

Vegetable Oils

Vegetable oil based fuels are biodegradable, non-toxic, and significantly reduce pollution. Plenty of experimental work has been carried out in various countries for utilization of vegetable oils in compression ignition engines. Vegetable oils and their derivatives in diesel engines lead to substantial reductions in sulphur, carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), smoke, noise, and particulate emissions. Furthermore, contribution of bio-fuels to greenhouse effect is insignificant, since carbon dioxide (CO_2) emitted during combustion is recycled in the photosynthesis process in the plants. Vegetable oils have about 10% lower heating value than diesel due to its oxygen content. The kinematic viscosity of vegetable oils is however several times higher than that of diesel. Higher viscosity of vegetable oils (35–45 cSt at 40°C) as against diesel (3-4 cSt at 40°C) leads to problems in pumping and atomization, ring-sticking, carbon deposits on the piston, cylinder head, ring grooves, etc. In addition, higher viscosity is responsible for various undesirable combustion features of straight vegetable oils. Since straight vegetable oils are not suitable as fuels for diesel engines, they have to be modified to bring their combustion related properties closer to mineral diesel. This fuel modification is mainly aimed at reducing the viscosity to get rid of flow/ atomization related problems. Four well-known techniques are proposed to reduce the viscosity levels of vegetable oils, namely heating/ pyrolysis, dilution/ blending, micro-emulsion, and transesterification [3].

In India, there is a massive movement underway towards commercial implementation of biodiesel as fuel however this involves chemical processing, input of fossil energy in chemical processing and use of primary alcohols. Instead of this, possibility is being explored for using straight vegetable oils in direct injection (DI) compression ignition engines without substantial hardware modification for applications in rural agricultural sector, where these vegetable oils are produced locally, thus avoiding transport, and fuel processing related costs. Vegetable oils can be used directly or blended with mineral diesel to operate diesel engines in variety of applications. It has been proved that use of 100% vegetable oils is also possible with some minor modifications in the fuel handling system [4].

In India, there is a tremendous interest to utilize non-edible vegetable oils and their derivatives as fuels in diesel engines. India is producing host of non-edible oils such as *Linseed, Castor, Jatropha, Karanja (Pongamia glabra), Neem (Azadirachta indica), Palash (Butea monosperma), Kusum (Schlelchera trijuga)* etc. Some of these oils are not being adequately utilized, and it has been estimated that some plant-based forest derived oils have a much higher production potential.

Vegetable oils as an alternative fuel have following advantages:

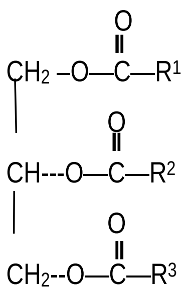
- Vegetable oils are locally available resources in rural areas.
- Development of bio-fuel industry would strengthen rural agricultural economy.
- These are biodegradable and non-toxic.
- These fuels have engine compatible fuel characteristics indicating a possibility of these being used as a diesel substitute with no/ very little hardware modifications.
- Low sulphur content fuels hence environment friendly.
- Enhanced fuel lubrication properties.
- Lower safety issues involved because of substantially higher flash points compared to mineral diesel.

- Vegetable oils have a reasonable cetane number and hence possess less knocking tendency.
- Low aromatic content and
- Vegetable oils help reduce costly petroleum imports.

In view of these advantages, Government of India is planning to use biofuels on a large scale. Indian Railway, the largest transport corporation in the world, is experimenting with Jatropha oil biodiesel to run passenger trains. Indian Railways' annual fuel (diesel) bill of Rs. 3400 crores could be lowered by nearly Rs. 300-400 crores annually by using vegetable oil derivative fuels.
For India, there is a need to take a mission approach to explore the possibility of using straight/ unmodified vegetable oils as fuel in order to reduce the pollution and increase the energy security of the country, especially in rural areas. It is suggested by 'Sustainable Transformation of Rural Areas' (SUTRA), IISc Bangalore that the vegetable oils like Jatropha and Karanja can be used directly in the engines without chemical processing, however detailed technical and scientific study in this regard using Indian origin vegetable oils is required.
There are various challenges in using vegetable oils as diesel fuels. These challenges are:

- The price of vegetable oil is dependent on the feedstock price.
- Feedstock homogeneity, consistency and reliability are questionable.
- Homogeneity of the product depends on the supplier, feedstock and production method used.
- Storage and handling is difficult (particularly stability on long-term storage).
- Flash point of blends is unreliable.
- Compatibility with materials used in IC engine needs to be investigated.
- Cold weather operation of the engine is not easy with vegetable oils.
- Acceptance by engine manufacturers is another major difficulty.
- Continuous availability of the vegetable oils needs to be assured before embarking on the large-scale usage in IC engines.

Vegetable Oil Chemistry: The petroleum diesel fuel molecules are saturated non-branched molecules with carbon atoms ranging between 12 and 18, whereas vegetable oils are the mixture of organic compounds ranging from simple straight chain compound to complex structure of proteins and fat-soluble vitamins. Fats and oils are primarily water-insoluble, hydrophobic substances in the plant and animal kingdom that are made up of one mole of glycerol and three moles of fatty acids and are commonly referred to as triglycerides. Vegetable oils are usually triglycerides generally with number of branched chains of different length, and have structure notation as shown:



Where R^1, R^2, R^3 represent hydrocarbon chain of acids.

Fatty acids vary in carbon chain length and in the number of unsaturated bonds (double bonds). The structures of common fatty acids are given in **Table** 1, and fatty acid compositions of some vegetable oils are given in **Table** 2.
Vegetable oils have about 10% less heating value than diesel oil due to the oxygen content in their molecule and the viscosity of vegetable oil is several times higher than that of mineral diesel oil due to its larger molecular weight and complex chemical structure. The fuel related properties (Physical and Thermal) of some of the vegetable oils are listed in **Table 3**.

Table 1: Chemical Structure of Common Fatty Acids [5]

Fatty acid	Systematic name	Structure [a]	Formula
Lauric	Dodecanoic	12:0	$C_{12} H_{24} O_2$
Myristic	Tetradecanoic	14:0	$C_{14} H_{28} O_2$
Palmitic	Hexadecanoic	16:0	$C_{16} H_{32} O_2$
Stearic	Octadecanoic	18:0	$C_{18} H_{36} O_2$
Arachidic	Eicosanoic	20:0	$C_{20} H_{40} O_2$
Behenic	Docosanoic	22:0	$C_{22} H_{44} O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24} H_{48} O_2$
Oleic	cis-9-Octadecenoic	18:1	$C_{18} H_{34} O_2$
Linoleic	cis-9,cis-12-Octadecadienoic	18:2	$C_{18} H_{32} O_2$
Linolenic	cis-9,cis-12, cis-15-Octadecatrienoic	18:3	$C_{18} H_{30} O_2$
Erucic	cis-13-Docosenoic	22:1	$C_{22} H_{42} O_2$

[a] xx:y indicates xx carbons in the fatty acid chain with y double bonds.

Table 2: Chemical Composition of Vegetable Oils [5]

Vegetable oil	Fatty Acid Composition, wt.%								
	14.0	16:0	18:0	20:0	22:0	24:0	18:1	22:1	18:2	18:3
Corn	0	12	2	Tr	0	0	25	0	6	Tr
Cottonseed	0	28	1	0	0	0	13	0	58	0
Crambe	0	2	1	2	1	1	19	59	9	7
Linseed	0	5	2	0	0	0	20	0	18	55
Peanut	0	11	2	1	2	1	48	0	32	1
Rapeseed	0	3	1	0	0	0	64	0	22	8
Safflower.	0	9	2	0	0	0	12	0	78	0
H.O. Safflower	Tr	5	2	Tr	0	0	79	0	13	0
Sesame	0	13	4	0	0	0	53	0	30	0
Soya bean	0	12	3	0	0	0	23	0	55	6
Sunflower	0	6	3	0	0	0	17	0	74	0
Rice-bran	0.4-0.6	11.7-16.5	1.7-2.5	0.4-0.6	-	0.4-0.9	39.2-43.7	-	26.4-35.1	-
Sal	-	4.5-8.6	34.2-44.8	6.3-12.2	-	-	34.2-44.8	-	2.7	
Mahua	-	16.0-28.2	20.0-25.1	0.0-3.3	-	-	41.0-51.0	-	8.9-13.7	-
Neem	0.2-0.26	13.6-16.2	14.4-24.1	0.8-3.4	-	-	49.1-61.9	-	2.3-15.8	-
Karanja	-	3.7-7.9	2.4-8.9	-		1.1-3.5	44.5-71.3	-	10.8-18.3	-

The high viscosity of vegetable oil, 35-60 cSt compared to 4 cSt for diesel oil at 40°C, leads to problem in pumping and spray characteristics (atomization & penetration etc.). The inefficient mixing of oil with air contributes to incomplete combustion. Higher flash point attributes to its lower volatility characteristics. This results in high carbon deposit formation, injector coking, piston-ring sticking, lubricating oil dilution and oil degradation. The combination of high viscosity and low volatility of vegetable oils cause poor cold starting, misfire and ignition delay related issues. Some of the short-term and long-term problems associated with utilization of vegetable oils in engine are shown in **Table 4**. This table also discusses probable reasons and potential solutions for these problems. Polyunsaturated nature of the vegetable oils causes long-term problems such as gum formation, ring sticking etc. Because of these problems, vegetable oils must be chemically modified to a more suitable and compatible fuel for existing engines.

Table 3: Physical and Thermal Properties of Vegetable Oils [5]

Vegetable oil	Kinematic viscosity*	Cetane no.	Heating value MJ/kg	Cloud point (°C)	Pour point (°C)	Flash point (°C)	Density Kg/l	Carbon residue Wt %	Ash Wt %	Sulfur Wt %
Corn	34.9	37.60	39.50	-1.1	-40.0	277	0.9095	0.24	0.010	0.01
Cotton-seed	33.5	41.8	39.5	1.7	-15.0	234	0.9148	0.24	0.010	0.01
Cramble	53.6	44.6	40.5	10.0	-12.2	274	0.9044	0.23	0.050	0.01
Linseed	22.2	34.6	39.3	1.7	-15.0	241	0.9236	0.22	<0.01	0.01
Peanut	39.6	41.8	49.8	12.8	-6.7	271	0.9026	0.24	0.005	0.01
Rapeseed	37.0	37.6	39.7	-3.9	-31.7	246	0.9115	0.30	0.054	0.01
Safflower	31.3	41.3	39.5	18.3	-6.7	260	0.9144	0.25	0.006	0.01
H.O. safflower	41.2	49.1	39.5	-12.2	-20.6	293	0.9021	0.24	<0.001	0.02
Sesame	35.5	40.2	39.3	-3.9	-9.4	260	0.9133	0.25	<0.01	0.01
Soyabean	32.6	37.9	39.6	-3.9	-12.2	254	0.9138	0.27	<0.01	0.01
Sunflower	33.9	37.1	39.6	7.2	-15.0	274	0.9161	0.23	<0.01	0.01
Palm	39.6	42.0	-	31.0	-	267	0.9180	-	-	-
Babassu	30.3	38.0	-	20.0	-	150	0.9460	-	-	-
Tallow	-	-	40.0	-	-	201	-	6.21	-	-

Table 4: Problems and potential solutions for using vegetable oils as engine fuels [6, 7]

Problem	***Probable cause***	***Potential solution***
Short-term		
1. Cold weather starting	High viscosity, low cetane, and low flash point of vegetable oils	Preheat fuel prior to injection. Chemically alter fuel to an ester
2. Plugging and gumming of filters, lines and injectors	Natural gums (phosphatides) in vegetable oil. Ash.	Partially refine the oil to remove gums. Filter to 4 microns
3. Engine knocking	Very low cetane of some oils. Improper injection timing.	Adjust injection timing. Preheat fuel prior to injection. Chemically alter fuel to an ester
Long-term		
4. Coking of injectors and Carbon deposits on piston and head of engine	High viscosity of vegetable oil, incomplete combustion of fuel. Poor combustion at part load	Heat fuel prior to injection. Switch engine to diesel fuel when operating at part load. Chemically alter the vegetable oil to an ester.
6. Excessive engine wear	High viscosity, incomplete combustion of fuel. Poor combustion at part load. Possibly free fatty acids in vegetable oil. Dilution of engine lubricating oil due to blow-by of vegetable oil.	Heat fuel prior to injection. Switch engine to diesel fuel when operating at part load. Chemically alter the vegetable oil to an ester. Increase lubricating oil changes. Lubricating oil additives to inhibit oxidation.
7. Failure of engine lubricating oil due to polymerization	Collection of poly-unsaturated vegetable oil blow-by in crank-case to the point where polymerization occurs	Same as in 6.

Straight vegetable oils are not suitable as fuel for diesel engines; hence they have to be modified to bring their combustion related properties closer to those of mineral diesel. This fuel modification is mainly aimed at reducing the viscosity to get rid of flow and combustion related problems. Considerable efforts have been made to develop vegetable oil derivatives that approximate the properties and performance of hydrocarbon based fuels. Vegetable oils can be used through at least four ways [8-12]:

- Direct use and blending
- Micro-emulsion
- Pyrolysis (thermal cracking)
- Transesterification

Jatropha Curcas (Physic Nut): Linnaeus (1753) was the first to name the physic nut Jatropha Curcas L. according to the binomial nomenclature of "*Species Plant Arum*". The genus name *Jatropha* derives from the Greek iatros (doctor) and trophe (food) which implies medicinal uses. According to Correll and Correll (1982), *curcas* is the common name for physic nut in Malabar, India.

Jatropha is a plant of Latin American origin, which is now widespread throughout arid and semi-arid tropical regions of the world including India. Jatropha has several advantages over other plants. It can thrive under adverse conditions. It is a drought-resistant, perennial plant, living up to fifty years and has capability to grow on marginal soils. Jatropha requires very little irrigation and grows in all types of soils and from coastline to hill slopes. **Figure 1** shows a typical Jatropha plant growing on rocks in mountainous regions.

Figure 1: Jatropha on Rocky Substrate

Many parts of the plants are used in traditional medicines. The physic nut, by definition, is a small tree or large shrub, which can reach a height of up to five meters. Jatropha oil is slow-drying oil, which is odourless and colourless, when fresh but becomes yellow after aging. Jatropha seeds are toxic to humans and animals. The toxicity is mainly due to the phorbol esters, curcin (toxic protein), diterpene esters, and other heat-sensitive anti-nutrients such as lectins, trypsin inhibitors etc.

The production of Jatropha seeds is about 0.8 kg per square meter per year. The oil content of Jatropha seed ranges from 30 to 40% (w/w) and the kernel itself ranges from 45 to 60% (w/w). The fact that the oil of Jatropha cannot be used for nutritional purposes without detoxification makes its use as energy/ fuel source very attractive. In Madagascar, Cape Verde and Benin, Jatropha oil was used as a diesel substitute during the Second World War.

Jatropha oil is also used as a purgative, to treat skin diseases and to soothe pain such as that caused by rheumatism. Various extract from Jatropha curcas seeds and leaves show molluscicidal, insecticidal and fungicidal properties. The press cake is valuable as organic manure since it has nitrogen content similar to that of seed cake of castor bean and chicken manure. Therefore, it is currently used as bio-fertilizer and bio-pesticide. The nitrogen content ranges from 3.2 to 3.8%, depending on the source.

Jatropha can also be planted in the form of hedge to protect gardens and fields from foraging animals and to prevent soil erosion as shown in **Figure 2**. It is a pest resistant plant and when planted as a fence, it repels rodents and has phyto-protective action against pests and pathogens and thus provides additional protection to intercropped plants. Jatropha plantations also attract nesting birds and honey. Various physical and chemical properties of Jatropha oil and Jatropha oil methyl ester (JOME) are given in **Table 5**.

Figure 2: Vegetables Intercropped between Rows of Jatropha Plants

Table 5: Chemical and Physical Properties of Jatropha Oil and JOME [7, 13-14]

Property	Jatropha	JOME	Diesel
Density at 15 °C (kg/m^3)	920	880	840
Flash point (°C)	210	170	86
Kinematic viscosity at 38 °C (cSt)	52	5.65	5.7
Pour point (°C)	-3	-	-15
Total acid number (mg KOH/g)	0.92	-	0.15-0.24
Cetane number	38	50-51	45-55
Specific gravity	0.918	-	0.867
API gravity	22.7	-	31.7
Calorific value (MJ/kg)	39.774	38.45	43.8
Saponification value	198	-	-
Iodine number	94	-	-
Carbon residue (%, w/w)	0.64	0.5	0.1
Sulphated ash (%, w/w)	-	0.014	-
Ester content (%, w/w)	-	99.6	-
Monoglycerides (%, w/w)	Not detected	0.24	-
Diglycerides (%, w/w)	2.7	0.07	-
Triglycerides (%, w/w)	97.3	Not detected	-

Jatropha sheds its leaves during dry season. It is, therefore, best adapted to arid and semi-arid conditions. It occurs mainly at lower altitudes (0-500 m) and therefore it is well adapted to higher temperatures regions. It is not sensitive to length of the day. It grows on well-drained soils with good aeration and is well adapted to marginal soils with low nutrient content. At least 2-3 tons of seeds/ hectare/ year can be harvested in semi-arid areas. The fruit is harvested by hand and fruit hulls and seeds are separated manually. Economic analyses have demonstrated that Jatropha oil can compete with diesel in villages. Jatropha based rural-economy system focuses on the use of this oil as a crucial element to activate a chain combining ecological, economic, and employment generating effects (specifically for women).
A naturally aspirated direct injection diesel engine is more sensitive to fuel quality due to the longer ignition delays and inferior performance of injection system. Jatropha oil has been considered potential alternative fuels for CI engines in the present experimental investigation. The main problem of using this oil in unmodified form in diesel engines is its high viscosity. Therefore, it is necessary to reduce the viscosity of the oil before injecting them in diesel engines. Various methods may be used to reduce the viscosity e.g., heating, blending, micro-emulsification, and transesterification. Transesterification is an effective method to improve the properties of vegetable oils but it needs chemical processing i.e., input of energy, alcohol, catalyst etc. hence leads to additional processing cost. In the present investigation, high viscosity of the oil was reduced by heating them (using waste heat of exhaust gases from the engine) and also by blending with diesel.

Engine Experimental Setup

Nearly all agricultural tractors pump sets, farm machinery, and transport vehicles use direct injection diesel engines. Keeping the specific features of diesel engines in mind, a typical engine system widely used in the agricultural sector in developing countries has been selected for present experimental investigations.

Engine: Four-stroke, single-cylinder, constant speed, water-cooled, direct injection diesel engines fitted with AC alternator of 7.4 kW (10 HP) rating (Make: Kirloskar Oil Engines Ltd. India, Model: DM-10) were procured to study the effect of heating and blending of the vegetable oils on performance and emissions of different fuels. The engines operated at a constant speed of 1500 rpm. The fuel injection pressure recommended by the manufacturer is in the range of 200-205 bars at 1500 rpm. Fresh lubricating oil was filled in oil sump before beginning the experiments.

Engine Alternator System: The engine is coupled with a single phase, 220 volts AC alternator. The alternator is used for loading the engine. When load bank is switched on, it consumes the electricity generated by the alternator. Alternator converts mechanical power produced by the engine to electricity and provides it to the load bank.

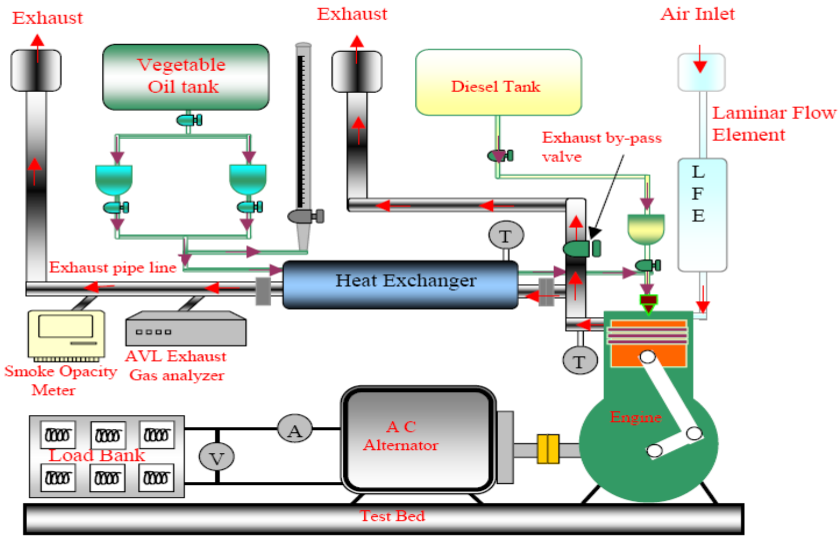


Figure 3: Schematic diagram of experimental setup

Figure 4: Experimental setup

Fuel Conditioning System: Fuel conditioning is essential because vegetable oil is highly viscous and contains impurities including dust particles, gums etc. Therefore, it is necessary to filter the vegetable oil adequately before it is supplied to the engine. If vegetable oil of poor quality is supplied to the engine then it may generate higher particulate matter leading to increased engine wear, apart from chocking of fuel lines, fuel pumps etc. In the experimental setup, two filters are provided at the exit of the tank and the one before fuel pump (**Figure 5**). These filters have to be changed once they are clogged. Two fuel filters are provided next to the fuel tank because if one filter is clogged, supply of fuel can be switched over to another filter while the clogged filter can be cleaned/ replaced and engine operation during this procedure is not affected.

Figure 5: Fuel filters

Two fuel tanks are given in the setup. One fuel tank is for diesel and another one for vegetable oil. The engine is started with mineral diesel and once the engine warms up, it is switched over to vegetable oil. After concluding the tests with vegetable oil, the engine is again switched back to diesel until the vegetable oil is purged from the fuel line, injection pump and injector in order to prevent deposits, and avoid cold starting problems.

Heat Exchanger: A shell and tube type heat exchanger is designed to preheat the vegetable oil using waste heat of the exhaust gases. Its construction is shown in **Figure 6**. Heat exchanger consists of one inner pipe and an outer shell. Fins were brazed to inner pipe to increase the heat transfer area between the two fluids (vegetable oil and exhaust gases). One supply pipe connection is provided in each side plate of the heat exchanger for inlet and outlet of vegetable oil. A thermocouple was provided in the heat exchanger to measure the temperature of the heated vegetable oil, close to the exit point.

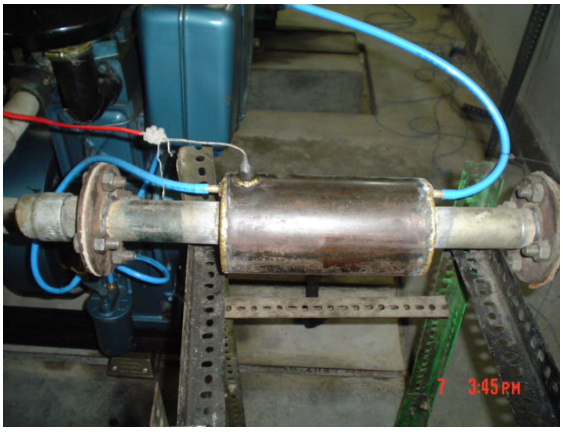


Figure 6: Heat exchanger

Exhaust gas opacity was measured using smoke opacimeter (Make: AVL Austria, Model: 437). The exhaust gas composition was measured using exhaust gas analyzer (Make: AVL India, Model: DIGAS 444). It measures CO_2, CO, HC, NO and O_2 concentrations in the exhaust gas. Measurement range and resolution for different gases by exhaust gas analyzer are given in **Table 6**.

Table 6: Exhaust gas analyzer specifications

Exhaust Gas	Measurement Range	Resolution	Accuracy
CO	0-10 vol.%	0.01 vol. %	< 0.6% vol: ± 0.03% vol. ≥ 0.6% vol: ± 5% of ind. val.
HC	0-20,000 ppm	≤ 2000: 1 ppm vol., > 2000: 10 ppm	< 200 ppm vol.: ± 10 ppm vol. ≥ 200 ppm vol: ± 5% of ind. val.
CO_2	0-20 vol.%	0.1 vol.%	< 10% vol: ± 0.5% vol. ≥ 10% vol: ± 5% of val. M.
O_2	0- 22 vol. %	0.01 vol.%	< 2% vol: ± 0.1% vol. ≥ 2% vol: ± 5% of val. M.
NO	0-5000 ppm	1 ppm vol	< 500 ppm vol: ± 50 ppm vol. ≥ 500 ppm vol: ± 10% of ind. val.

Higher viscosity is a major problem in using vegetable oil as fuel for diesel engines. In the present investigations, viscosity of vegetable oils was reduced by (i) heating and (ii) blending the vegetable oil with mineral diesel. Higher viscosity is a major problem in using vegetable oils as fuel for diesel engines. In the present investigations, viscosity was reduced by (i) heating and (ii) blending the vegetable oil with mineral diesel. Viscosity of Jatropha oil was measured at different temperatures in the range of 40-100°C (**Figure 7**). Viscosity of Jatropha oil decreases remarkably with increasing temperature and it becomes close to mineral diesel at temperatures above 90°C (within ASTM limits). Viscosity of diesel was 2.44 cSt at 40°C. For Jatropha oil, viscosity was found below 6 cSt at a temperature above 90°C. Therefore, Jatropha oil should be heated to 90ºC before being injected into the CI engine in order to bring its physical properties and spray characteristics closer to mineral diesel.

The viscosity of various blends of Jatropha oil and mineral diesel was evaluated at 40°C and is shown in **Figure 7**. Viscosity of Jatropha oil decreases after blending (**Figure 7b**). The viscosity of 30:70 and 20:80 blends was slightly higher than mineral diesel but these blends are within ASTM limits for viscosity. For these two Jatropha oil blends, corresponding viscosity was found to be 5.35 and 4.19 cSt respectively.

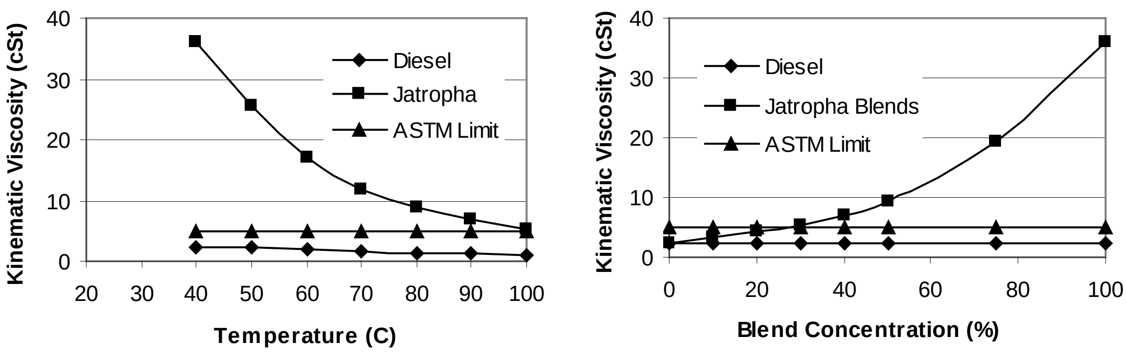


Figure 7: Effect of (a) temperature and (b) blending on viscosity of Jatropha oil

Performance & Emission Tests for Jatropha Oil (Pre-heated & Unheated)

Engine tests were conducted for performance and emissions using unheated Jatropha oil and preheated Jatropha oil. The baseline data was generated using mineral diesel. The performance and emissions characteristics of these fuels are shown in the **Figure 8**.

Mineral diesel fuelling results in lowest BSEC. For Jatropha oil, BSEC was found slightly higher compared to diesel. Lower calorific value of Jatropha oil leads to increased fuel flow in order to maintain similar energy input to the engine. Thermal efficiency of preheated Jatropha oil was found slightly higher than unheated oil. The possible reason may be relatively improved fuel atomization and combustion along with additional lubricity of Jatropha oil. Vegetable oil contains oxygen in their molecules, which may be possible reason for improved combustion. However, thermal efficiency for unheated Jatropha oil was slightly lower than mineral diesel. The possible reason may be higher fuel viscosity. Higher fuel viscosity results in larger fuel droplets followed by inadequate mixing of fuel and air. **Figure 8** also shows higher exhaust gas temperatures of the preheated Jatropha oil over other fuels at higher engine loads. Unheated Jatropha oil shows exhaust temperatures lower than preheated Jatropha oil but higher than mineral diesel. Possibly, higher ignition delay associated with Jatropha oil results in delayed combustion and higher exhaust gas temperature.

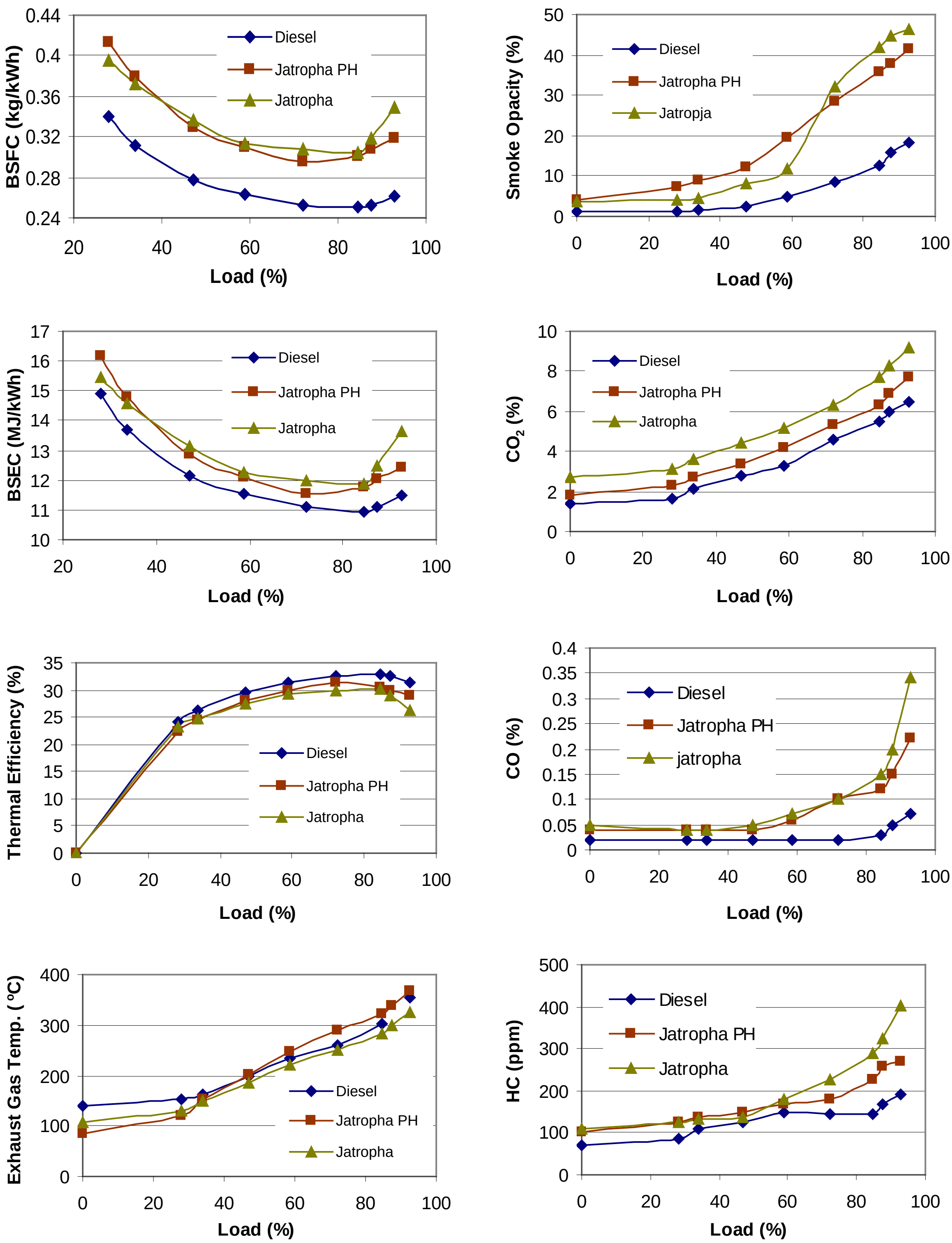


Figure 8: Performance and emissions characteristics for Jatropha (unheated and preheated) vis-à-vis mineral diesel

Smoke opacity for Jatropha oil operations (both heated and unheated) was greater than that of mineral diesel. Heating the Jatropha oil result in relatively lower smoke opacity compared to unheated oil but it is still higher than diesel. Preheated Jatropha oil shows marginally higher CO_2 emission compared to mineral diesel, because of higher BSEC. Unheated fuel operation showed still higher CO_2 emissions compared to heated Jatropha and mineral diesel. At lower loads, CO emissions were nearly similar for all fuels but at higher loads, CO emissions were found to be higher for Jatropha oil compared to mineral diesel. This is possibly a result of poor spray atomization and non-uniform mixture preparation of Jatropha oil at higher engine loads, when larger quantity of fuel in injected into constant amount of air. However, heating the Jatropha oil results in relatively lower CO emission compared to unheated Jatropha oil. The HC emissions are lower at partial load, but tend to increase at higher engine loads for all fuels. This is due to lack of oxygen resulting from engine operation at higher equivalence ratio. Diesel fuel operation produces relatively lower HC emissions compared to Jatropha oil. All the experimental results suggest that heating the Jatropha oil using exhaust gases improves their engine performance and emissions and bring their combustion properties closer to mineral diesel.

Long-Term Endurance Test for SVO

In the long-term endurance test, the effect of use of SVO's and their blends on various engine parts vis-à-vis mineral diesel fuel were studied. For this purpose, two new identical engines were subjected to similar loading cycles and operating conditions with different fuels. The assessment of wear of various parts of 100% Jatropha, and diesel-fuelled engines was done in long-term endurance test after dismantling various parts of the engine. Various tests on the two engine systems are conducted as per the procedure specified in IS10000: 1980.

After the completion of Preliminary running in and fuel consumption test, the engines were dismantled completely and examined physically for the conditions of the various critical parts before endurance test was commenced. After physical examination, the dimensions of various moving, vital parts were recorded e.g. cylinder head, cylinder bore/ cylinder liner, piston, piston-rings, gudgeon pin, valves (inlet and exhaust), valve seats (inserts), valve guide, valve springs, connecting rod, big-end bearing, small-end bush, connecting rod bolts and nuts, crankshaft, crankshaft bearings and journals, and camshaft etc. The engines were re-assembled and mounted on suitable test beds and again run-in for 12 hours as recommended by the manufacturer. This test was carried out to take care of any misalignments occurring during dismantling and re-assembling of the engine. This test included eleven hours of continuous run, at rated full load at the rated speed followed by one hour run at 10% overload. During the running-in period, none of the critical components listed above were replaced. The lubricating oil from the oil sump was drained off and the engine was refilled with SAE 30 grade fresh lubricating oil as specified by the manufacturer.

The engines were run for 32 cycles (each of 16 hours continuous running) at rated speed. The test cycle followed is specified in the **Table 7**.

Table 7: Test cycle for long-term endurance test

Load (% of rated load)	Running time (Hours)
100	4
50	4
110	1
No load (Idling)	0.5
100	3
50	3.5

Visual Inspection of Vital Engine Parts

The physical conditions of various vital engine parts before and after the endurance test are shown in **Figure 9**. **Figure 9** shows the condition of new parts before the endurance test was commenced (after initial running in) as well as after the completion of long-term endurance test (i.e. after 512 hours). An important observation during this test was that the injector tip of the preheated Jatropha fuelled engines were cleaned three times during the total duration of 512 hours. During the period of endurance test, mineral diesel fuelled injector tips were not cleaned throughout the test period. Hence no definite conclusion can be drawn from injector tip deposit of the engines however it can be concluded that 100% Jatropha oil are comparatively problematic from injector tip deposit point of view.

Before the Endurance Test		After the Endurance Test	
Diesel	100% Jatropha	Diesel	100% Jatropha

Figure 9: Vital engine parts of the engines before and after the long-term endurance test

Conclusions

In the present investigations, non-edible Jatropha oil has been appropriately utilized by way of heating. Jatropha oil is selected for present investigation, since this is available in large surplus quantities in India and is essentially non-edible in nature. Jatropha oil is being singled out for large-scale plantation on wastelands in India. Nearly all agricultural tractors pump-sets, farm-machinery, and transport vehicles have direct injection diesel engines. Keeping specific features of diesel engines in mind, a typical engine system (4-stroke, single cylinder, constant speed, direct injection, compression ignition, 7.4 kW rated power, 948 cc), which is widely used in the agricultural sector in developing countries like India has been selected for the present experimental investigations.

For heating the vegetable oils which have very high viscosity at room temperature, waste heat of exhaust gas was utilized and a hardware (counter-flow heat exchanger) was developed for this purpose, which will cost approximately rupees 500 (on mass production). This heat exchanger can be added on to the existing engine system in the exhaust pipe very easily and the engine can then be operated successfully on viscous fuels such as vegetable oils.

The optimization of fuel injection pressure was carried out by conducting detailed engine tests on various fuel injection pressures for fuel economy and lowest emissions. Based on the results of BSFC, thermal efficiency, and smoke opacity, 200 bars was found to be optimum fuel injection pressure for unheated/ heated Jatropha oil. Heating the vegetable oils reduces the viscosity of Jatropha oil and brings it within the range of mineral diesel. Therefore the

optimum fuel injection pressure for Jatropha is taken as 200 bars and for mineral diesel, it is also 200 bars.
After optimization of fuel injection pressure, experiments were conducted to evaluate the effect of straight vegetable oils (heated and unheated) on performance and emissions of the CI engines vis-à-vis mineral diesel. Viscosity of the vegetable oils reduced by heating and by blending with mineral diesel. It was found that heating the Jatropha oil between 90-100°C is adequate to bring down the viscosity in close range to that of mineral diesel. Viscosity of Jatropha blends (up to 30%) was also found very close to diesel. Preheating the vegetable oil reduces the viscosity and it does not lead to change in optimum fuel injection pressure. Blending of Jatropha oil with mineral diesel up to 20% (J20) also deliver acceptable engine performance and emission characteristics.
In the long-term endurance test, the effect of use of SVO's on various engine parts vis-à-vis mineral diesel fuel were studied. For this purpose, two new identical engines were subjected to similar loading cycles and operating conditions with different fuels. The long-term endurance tests were conducted in two phases. The assessment of wear of various parts of 100% Jatropha, and diesel-fuelled engines was done. All the vital dimensions were also recorded for assessment of engine wear.
After completion of the long-term endurance test, visual inspection was done for deposit assessment. In visual inspection of engine vital parts, slightly higher amount of carbon deposits on the vegetable oil fuelled engines compared to mineral diesel was observed. However it was also noticed that none of the engines demonstrated order of magnitude higher amount of carbon deposits, which are expected (and also reported in literature) from the SVO fuelled engine. This indicates that the pre-heating technology is successful in using SVO's as an alternate CI engine fuel; however, a revised maintenance schedule needs to be followed for this purpose. The piston rating of the four engines reflects that the SVO fuelled engines have reasonably acceptable long-term performance. The engines are expected to operate even more successfully after modification in the maintenance schedule, which is prescribed by the manufacturer.

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