

Scope and Limitations of Utilisation of Non-edible Vegetable Oils as a Substitute Fuel for Diesel Engines – An Experimental Study

(2005-2008)

Principle Investigator

Dr. Avinash Kumar Agarwal

*Engine Research Laboratory,
Department of Mechanical Engineering*



Indian Institute of Technology Kanpur

For India, there is a need to take a mission approach to explore the possibility of using straight/ unmodified vegetable oils/ their blends with mineral diesel as alternative fuel in order to reduce the pollution and to increase the energy security of the country, especially in rural areas. This DST TSG sponsored project was aimed at exploring technical feasibility of using straight vegetable oils (Jatropha and Karanja) in direct injection compression ignition engine without major hardware modifications. Since use of unprocessed straight vegetable oils has its own merits, it was decided to examine two most commonly available oils (in unmodified form) in an unmodified constant-speed direct-injection diesel engine typically used in the agricultural sector in India. Study was carried out in two phases for (i) Straight vegetable oils and their higher blend, and (ii) lower blends of vegetable oils. This project is carried out at Engine Research Laboratory, Indian Institute of Technology Kanpur.

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 was selected for the present experimental investigations. For preheating the vegetable oils, which have very high viscosity at room temperature, waste heat of exhaust gas was utilized and hardware (counter-flow heat exchanger) was developed for this purpose. 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.

Initially, detailed tests were conducted to characterize vegetable oils vis-à-vis mineral diesel in order to compare various physical, chemical, and thermal properties such as density, API gravity, kinematic viscosity, cloud and pour point, carbon residue, ash content, aniline point, diesel index, flash point and calorific value. Kinematic viscosity of straight vegetable oil is significantly higher (order of magnitude) than mineral diesel however heating these vegetable oils up to 90-100°C or

blending them with mineral diesel (< 30%) will resolve the problem of high viscosity and bring the viscosity levels within the prescribed ASTM limits for CI engine fuels. Ash content and Conradson carbon residues are also higher for vegetable oils compared to mineral diesel, hence SVO fuelled engines emit higher particulate. These are the properties, which essentially pose serious challenges in utilization of SVO's as CI engine fuels. The calorific value of SVO's is approximately 10% lower than mineral diesel because of the presence of oxygen (\cong 10% w/w) in their molecular structure. Also, cetane number of SVO's is found to be slightly lower than mineral diesel. On blending SVO's in lower concentration (5% or 10%) with mineral diesel, all these relevant properties come very close to those of mineral diesel properties, thus lower blends do not pose any major operational challenge.

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. 200 bars was found to be optimum fuel injection pressure for unheated/ heated Jatropha oil, and 200-220 bars for unheated/ heated Karanja oil. 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. 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 were evaluated in the two phases. For this purpose, four new identical engines were subjected to similar loading cycles and operating conditions with different fuels. The assessment of wear of various parts of 50% Jatropha, 100% Jatropha, 100% Karanja and diesel-fuelled engines was done in Phase I where the fuel is preheated using waste heat of the engine exhaust and 5% Jatropha, 10% Jatropha and 10% Karanja vis-à-vis mineral diesel fuelled engines in Phase II of long-term endurance test, where the fuel viscosity is reduced by higher degree of blending with mineral diesel. In visual inspection of engine vital parts after phase I, slightly higher amount of carbon deposits on the three vegetable oil fuelled engines compared to mineral diesel was observed. However it was also noticed that none of these 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 lubricating oil samples were drawn from the engine after every 128 hours and various oil tribology related tests were conducted on these samples. Tribological tests conducted on the lubricating oil samples indicated that the SVO fuelled engine first undergo lowering of lubricating oil viscosity followed by severe vegetable oil initiated oxidation of lubricating oil base-stock and thus the life of the lubricating oil gets depleted in approximately 400 hours. It was also observed that the wear of Jatropha and Karanja engine liners is relatively higher compared to mineral diesel fuelled engine. However the wear of 50% Jatropha blend fuelled engine liner is found to be relatively lower compared to mineral diesel fuelled engine.

Long-term endurance tests of phase II for lower vegetable oil blends (J5, J10 and K10) vis-à-vis mineral diesel showed relatively higher carbon deposits on piston top. It was seen from the overall merit rating that the rating of the piston using vegetable oil blends as fuel was inferior to that from mineral diesel. Overall results suggested that K10 blend demonstrated relatively inferior engine performance compared to J5, J10 and mineral diesel and it gave poorest piston rating results as well. The oil samples were drawn from the engine after every 128 hours and various oil tribology related tests were conducted on these samples. It was observed that the liner wear is relatively higher in 10% Karanja oil compared to mineral diesel. The vegetable oils/ blends of Phase I and Phase II demonstrated identical copper corrosion potential of lubricating oil similar to that from mineral diesel fuelled engine, which is acceptable. Pentane and benzene insoluble in the lubricating oil samples of SVO fuelled engines is comparable to diesel fuelled engine. Observations of this test in phase II suggest that

even smaller concentration of vegetable oils in the fuel accelerates the polymerization of lubricating oil therefore there is a need to develop specialty lubricants for vegetable oil utilization in engines.

Investigations have been carried out to examine the comparative combustion characteristics using straight vegetable oils and their lower blends vis-à-vis mineral diesel. A careful analysis of cylinder pressure rise, heat release (instantaneous and cumulative) as well as other combustion parameters such as in-cylinder peak pressure, rate of pressure rise, crank angle at which peak pressure occurs, mass burning rates etc. was carried out from the observed data. Experiments show that the combustion phases are almost similar for vegetable oils/ blends and mineral diesel. SVO's shows lower combustion delay however slower heat release rate vis-à-vis mineral diesel. Combustion duration for SVO's is higher than mineral diesel and it increases as engine load increases. The effect of heating the vegetable oil is actually found to be different for Jatropha and Karanja oil. It was observed that on heating the Jatropha oil, the combustion duration actually increases and its becomes much higher than mineral diesel, whereas in case Karanja oil, on preheating the Karanja oil, the combustion duration becomes smaller compared to unheated Karanja oil. This effect is attributed to the difference in composition of the two oils. Summarily, no undesirable combustion features were observed in any of the fuels (SVO's and blends) therefore there is no operational problem expected from utilisation of the SVO's in CI engines from combustion point of view. It is only deposits and durability issues that pose challenge and can be handled easily by fuel pre-heating using the waste heat of the exhaust gas and use of speciality lubricants.

Hence overall, both the approaches have been successfully used for operating the engines with minor addition of hardware. Based on the knowledge gained from the experiments, an engine system having all the necessary arrangements for practical use in the field has been prepared. The owner has to spend approximately Rs 2000 in purchasing the heat exchanger and other hardware/ mounting/ stand etc. to make his engine compatible to SVO's.



Engine Setup for Using SVO as Fuel

Findings/ Conclusions of the Project

In the present investigations, non-edible oils have been appropriately utilized by way of heating and blending for running diesel engine. Jatropha and Karanja oils are selected for present investigation, as these are available in large surplus quantities in India and are 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.

Firstly, detailed tests were conducted to characterize vegetable oils vis-à-vis mineral diesel in order to compare various physical, chemical, and thermal properties such as density, API gravity, kinematic viscosity, cloud and pour point, carbon residue, ash content, aniline point, diesel index, flash point and calorific value. Density of vegetable oils is found to be higher than mineral diesel. Kinematic viscosity of straight vegetable oil is significantly higher (order of magnitude) than mineral diesel however heating these vegetable oils up to 90°C or blending them with mineral diesel (< 30%) will resolve the problem of high viscosity and bring the viscosity levels within the prescribed ASTM limits for CI engine fuels. Cloud and pour point temperature, flash and fire point temperatures and carbon residue of straight vegetable oils are found to be significantly higher than mineral diesel. In addition, ash content and Conradson carbon residues are also higher than mineral diesel, thus SVO fuelled engines will emit higher particulate. These are the properties, which will essentially pose serious challenges in utilization of SVO's as CI engine fuels. The calorific value of SVO's is approximately 10% lower than mineral diesel because of the presence of oxygen ($\cong 10\%$ w/w) in their molecular structure. Cetane number of SVO's is found to be slightly lower than mineral diesel. On blending SVO's in lower concentration (5% or 10%) with mineral diesel, all these relevant properties come very close to those of mineral diesel properties, thus lower blends are not expected to pose any major operational challenge. The oxidation stability test conducted on Jatropha oil did not show any problem related to storage stability and it passed the Rancimat test.

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, and 200-220 bars for unheated/ heated Karanja oil. Heating the vegetable oils reduces the viscosity of Jatropha and Karanja oil and brings it within the range of mineral diesel. Therefore the optimum fuel injection pressure for Jatropha is taken as 200 bars, for Karanja oil, it is 200/220 bars whereas for mineral diesel, it is 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 and Karanja oil between 90-100°C is adequate to bring down the viscosity in close range to that of mineral diesel. Viscosity of Jatropha and Karanja 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 and Karanja oils 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 and their blends on various engine parts vis-à-vis mineral diesel fuel were studied in two different phases. For this purpose, four 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 50% Jatropha, 100% Jatropha, 100% Karanja and diesel-fuelled engines was done in Phase I where the fuel is preheated using waste heat of the engine exhaust and 5% Jatropha, 10% Jatropha and 10% Karanja and diesel fuelled engines in Phase II of long-term endurance test, where the fuel viscosity is reduced by higher degree of blending with mineral diesel. These tests were executed with new vital engine parts for each phase and after necessary running in of the engine. 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 after phase I, slightly higher amount of carbon deposits on the three vegetable oil fuelled engines compared to mineral diesel was observed. However it was also noticed that none of these 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. Results of carbon deposit tests showed relatively higher amount of carbon deposits on the piston top for vegetable oil fuelled engines therefore the piston rating was carried out. 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. The lubricating oil samples were drawn from the engine after every 128 hours and various oil tribology related tests were conducted on these samples. Tribological tests conducted on the lubricating oil indicated that the SVO fuelled engine first undergo lowering of lubricating oil viscosity followed by severe vegetable oil initiated oxidation of lubricating oil base-stock and thus the life of the lubricating oil is depleted in approximately 400 hours. It was also observed that the wear of Jatropha and Karanja engine liners is relatively higher compared to mineral diesel fuelled engine. However, the wear of 50% Jatropha blend fuelled engine liner is found to be relatively lower compared to mineral diesel fuelled engine.

Long-term endurance tests of phase II for lower vegetable oil blends (J5, J10 and K10) vis-à-vis mineral diesel showed relatively higher carbon deposits on piston top in case of SVO blend operated engines. Piston rating tests are conducted to analyze the carbon and lacquer deposited on the piston from these engines. It was seen from the overall merit rating that the rating of the piston using vegetable oil blends as fuel was inferior to that from mineral diesel. Overall results suggested K10 blend demonstrated relatively inferior engine performance compared to J5, J10 and mineral diesel and it gave poorest piston rating results as well. K10 engine piston had higher carbon deposits at the skirt region, ring-groove region, under-crown and under-skirt regions. The oil samples were drawn from the engine after every 128 hours and various oil tribology related tests were conducted on these samples. Density of lubricating oil from 10% Karanja fuelled engine is significantly higher than diesel, 5% and 10% Jatropha fuelled engine after 512 hours, which indicates possibly higher rate of engine wear in 10% Karanja fuelled engine. 10% Karanja fuelled engine also showed increase in kinematic viscosity of lubricating oil after 512 hours of usage while diesel, 5 and 10% Jatropha fuelled engines showed decrease in kinematic viscosity. Jatropha blend fuelled engine's lubricating oil showed lower ash content compared to 10% Karanja and diesel-fuelled engines. Hence lubricating oil composition should be different for Karanja blend fuelled engines keeping the chemical species formation/

base-stock polymerization, which is leading to increase in viscosity with time. The surface profile of all the liner surfaces was done to observe their relative wear pattern. It was observed that the liner wear is relatively higher in 10% Karanja oil compared to mineral diesel. However, the wear pattern observed with 5% and 10% Jatropha oil are almost identical to mineral diesel.

The copper corrosion tests on the lube oil samples suggest that the vegetable oil blends of Phase I and Phase II demonstrate identical copper corrosion potential of lubricating oil as that of lubricating oil from mineral diesel which is acceptable. It can be concluded that SVO/ blends are as safe for engines as diesel from copper corrosion point of view. Pentane and benzene insoluble in the lubricating oil samples of SVO fuelled engines is comparable to diesel fuelled engine. After 512 hours slightly, more amount of cross-linked polymers are formed in SVO fuelled engines in comparison to diesel engine due presence of oxygen in these fuels which enhances the oxidation rate of lubricating oil. Jatropha (J100) and Karanja (K100) both exhibit similar effect on cross linked polymer formation in lubricating oils. Overall, it can be safely concluded that J50 and K100 show higher tendency for polymerization (of lubricating oil), compared to lower blends concentrations. After 512 hours slightly, more amount of cross-linked polymers are formed in SVO blend fuelled engines (Phase II) in comparison to diesel engine due presence of oxygen in these fuels which enhances the oxidation rate of lubricating oil. Observations of this test in phase II suggest that even smaller concentration of vegetable oils in the fuel accelerates the polymerization of lubricating oil therefore there is a need to develop specialty lubricants for vegetable oil utilization in engines as fuel. FTIR, Differential scanning calorimetry, Thermo-gravimetric analysis results indicated change in the chemical properties of lubricating oil with usage. More exhaustive chemical speciation of vegetable oil and its effect on lubricating oil will help formulation of specialty lubricating oils for SVO and vegetable oil blend fuelled engine.

Investigations have been carried out to examine the comparative combustion characteristics of a direct injection, constant-speed, compression ignition engine operating with straight vegetable oils and their lower blends vis-à-vis mineral diesel. Engine tests were performed at different engine loads ranging from no load to rated (100%) load at constant engine speed of 1500 rpm. A careful analysis of cylinder pressure rise, heat release (instantaneous and cumulative) as well as other combustion parameters such as in-cylinder peak pressure, rate of pressure rise, crank angle at which peak pressure occurs, rate of pressure rise, mass burning rates etc. was carried out from the observed data.

Experiments show that the combustion phases are almost similar for vegetable oils/ blends and mineral diesel. SVO's shows lower combustion delay however slower heat release rate vis-à-vis mineral diesel. Combustion duration for SVO's is higher than mineral diesel and it increases as engine load increases. Maximum in-cylinder pressure was observed to be higher for mineral diesel under all engine operating conditions, but J5 shows slightly higher peak pressure at times, whereas other blends were on lower side. Detailed combustion analysis suggests that J5 to J20 gives identical combustion as that of mineral diesel in the unmodified engine to partially replace mineral diesel without engine hardware modification.

The effect of heating the vegetable oil is actually found to be different for Jatropha and Karanja oil. It was observed that on heating the Jatropha oil, the combustion duration actually increases and its becomes much different than mineral diesel, whereas in case Karanja oil, on preheating the vegetable oil, the combustion duration becomes smaller compared to unheated Karanja oil. This effect is attributed to the difference in composition of the two oils. Summarily, no undesirable combustion features were observed in any of the fuels (SVO's and blends) therefore, there is no operational problem expected from combustion of the SVO's in CI engine point of view. It is only deposits and durability that poses this challenge and can be handled easily by fuel pre-heating using the waste heat of the exhaust gas.

Recommendations of the Project

1. It is possible to operate engines (Constant speed CI engines) with straight vegetable oils and blends by preheating and preconditioning of the vegetable oils and by changing the maintenance schedule, and changing to specialty lubricants, without deteriorating their operational durability. IIT Kanpur has developed a hardware, which will cost approximately Rs 500 (on mass production) and it can be added on to the engine for successfully using the vegetable oils in the engine.
2. SVO/ SVO blends up to 50% are extremely safe for engine operation with pre-heating, in terms of performance, endurance and adverse effects on lubricating oils. In our opinion, SVO/ SVO blends will not require any modification in fuel injection pressure, and engine hardware and will perform satisfactorily on all performance and endurance criteria.
3. The wear of the liner with engines operating on SVO were quite comparable to diesel engine therefore preheating the vegetable oil or blending with mineral diesel in lower concentration eliminates the problems of higher wear of cylinder liner and rings.
4. The lubricating oil however will be required to have a new formulation suitable to combat highly oxidizing and polymer formation properties of vegetable oils. The oil companies will need to come out with newer additive packages suitable for SVO fuelled engines. The present generation lubricating oils will deplete their useful life in approximately 400 hours.
5. One can use SVO by pre-heating or one can blend it with mineral diesel (up to 10% and no pre-heating) and these fuels will work satisfactorily in unmodified engines.

Disclaimer : *"The findings presented above are based on investigations carried out at IIT-Kanpur under a DST funded project. While the project findings have been peer reviewed and termed acceptable by the Committee, DST bears no responsibility for the accuracy of the results or any consequent losses due to implementation of these findings."*