2.1 INTRODUCTION

Biodiesel is defined as the fatty acid alkyl esters of vegetable oils, animal fats or waste oils. It is a technically competitive and environmental friendly alternative to conventional petro diesel fuel for use in compression-ignition (diesel) engines Knothe (2005) and Mittelbach & Remschmidt, (2004). Biodiesel is biodegradable, renewable, and non-toxic, possesses inherent lubricity, a relatively high flash point, and reduces most regulated exhaust emissions in comparison to petro diesel.

The use of biodiesel reduces the dependence on imported fossil fuels, which continue to decrease in availability and affordability. Vegetable oils for biodiesel production vary considerably with location according to climate and feedstock availability. Generally, the most abundant vegetable oil in a particular region is the most common feedstock.

Thus, rapeseed and sunflower oils are predominantly used in Europe; palm oil predominates in tropical countries, and soyabean oil and animal fats in the USA according to Sharp, Thomas, Ryan & Knothe G (2005) and Mittelbach & Remschmidt (2004). However, biodiesel production from conventional sources (soyabean, rapeseed, palm, etc.) increasingly has placed a strain on food production, price and availability Torrey (2007).
Therefore, the search for additional regional biodiesel feedstocks is an important objective.

Some recent examples, studies of biodiesel from less common or unconventional oils include tobacco Usta (2005), Pongamia Karmee & Chadha (2005), Jatropha Foidl (1996), rubber seed Ikwuagwu et al (2000), and Ramadhas et al (2005) oils. The Moringaceae is a single-genus family of oilseed trees with 14 known species. Of these, Moringa oleifera, which ranges in height from 5 to 10 m, is the most widely known and utilized Morton (1991) and Sengupta & Gupta (1970). M. oleifera, indigenous to sub-Himalayan regions of northwest India, Africa, Arabia, Southeast Asia, the Pacific and Caribbean Islands and South America, is now distributed in the Philippines, Cambodia and Central and North America Morton (1991). In Pakistan, M. oleifera is widely grown in the Punjab plains, Sindh, Baluchistan, and in the Northwestern Frontier Province Qaiser (1973).

It thrives best in a tropical insular climate and is plentiful near the sandy beds of rivers and streams Council of Scientific and Industrial Research (1962). The fast growing, drought-tolerant M. oleifera can tolerate poor soil, a wide rainfall range (25 to 300+ cm per year), and soil pH from 5.0 to 9.0 Palada & Changl (2003). When fully mature, dried seeds are round or triangular shaped, and the kernel is surrounded by a lightly wooded shell with three papery wings Council of Scientific and Industrial Research (1962) Sengupta & Gupta (1970), Qaiser (1973).

M.oleifera seeds contain between 33 and 41% w/w of vegetable oil Sengupta and Gupta (1970). Several authors investigated the composition of M. oleifera, including its fatty acid profile Anwar & Bhanger (2003), Anwar et al (2005), Sengupta & Gupta (1970), and Somali et al (1984).
Biodiesel can be used in neat form or blended with petroleum diesel for use in diesel engines. Its physical and chemical properties as it relates to operation of diesel engines are similar to petroleum based diesel fuel. It is non-hazardous and biodegradable.

Vegetable oils are good alternatives to fossil fuels for use in diesel engines. They are particularly attractive for agricultural applications. Since vegetable oils have properties comparable to diesel, they can be used to run compression ignition engines with little or no modifications. Engines using vegetable oils can produce the same power output, however, with reduced thermal efficiency and increased emissions (particularly smoke). Further vegetable oils lead to problems of gum formation and sluggish combustion. Several studies have been conducted to improve the performance of engines fuelled by vegetable oils.

Modifications like preheating the oil, use of hot surface ignition, converting the oil into its esters have been found to be effective. Investigations carried out on a variety of vegetable oils like Karanji oil, Ricebran oil, Rape seed oil etc. and their esters have shown that the methyl ester of vegetable oils offers lower smoke and higher thermal efficiency than the pure oil itself. However, conversion of vegetable oils into their esters is a complex process and time consuming. Rudolf Diesel, the inventor of the diesel engine, used plant oil to run his first diesel engine (1895). He demonstrated his new engine with peanut oil at the world exhibition (1900) in Paris and thus its history started there. In view of the oil crisis gripping the world, attention of the scientists and engineers of various places has been focused on alternative sources of energy in recent years. The seeds are pongamia, jetropa, peanut, etc.

Rural Indians have a potential substitute for diesel right in their backyards, claim the scientists at the Bangalore-based Indian Institute of
Science. They have shown that the oil extracted from seeds of Honge tree (pongamia pinnata, karanj tree in hindi) found all over the country can power existing diesel engines without causing pollution. One ton of seeds yield 0.25 ton of biofuel, according to Udipi Shrinivasa, Professor of Mechanical Engineering at the IISc. He says that 10 million hectares of plantation would lead to generation of 100 billion kW hr of electricity or replace 25 million tons of diesel that India imports. Honge oil works out to be 25 percent cheaper than diesel since the seed cake, after extracting oil, can be sold as fertilizer. Shrinivasa and his team reported in the current science.

Efforts to replace the fossil diesel fuel by plant oil as a renewable fuel started after two energy crises faced during the years 1973 and 1978. Murphy (1990) has reported on plants which are rich in triglycerides. Winkler et al (1997) have reported enzyme-supported extraction from jatropha curcas seed. Ma & Ilanna (1999) have reviewed the research and development work on biodiesel.

Samukawa et al (2000) have reported the use of immobilized lipase from Candida Antarctica for the production of biodiesel from plant oil. Among the plant sources, jatropha was chosen by UNIDO, U.S. and other countries for biodiesel production (2001). The US energy department has also felt that jatropha could meet the energy needs because it meets most of the fuel properties of petroleum based diesel. Most major European vehicle manufacturers now provide vehicle warranties covering the use of pure biodiesel through that might not be just any biodiesel.

Germany has more than 1500 filling stations supplying biodiesel and it’s cheaper than ordinary diesel fuel. It is widely used in France which is also the world’s largest producer of biodiesel. Virtually, all fossil diesel fuel sold in France contains biodiesel ranging between 2-5%. In the United Kingdom, biodiesel is to be taxed less than petro-diesel and it is already
available at fuelling stations. Biodiesel is more expensive than ordinary diesel in US, but sales are rising as fast as the prices are coming down.

Issariyakul et al (2007) studied Transesterification of waste fryer grease (WFG) containing 5–6 wt.% free fatty acid (FFA) was carried out with methanol, ethanol, and mixtures of methanol/ethanol maintaining the oil to alcohol molar ratio of 1:6 and initially with KOH as a catalyst. Mixtures of methanol and ethanol were used for transesterification in order to use the better solvent property of ethanol and rapid equilibrium using methanol. Formation of soap by reaction of FFA present in WFG with KOH instigated difficulty in the separation of glycerol from biodiesel ester. To untangle this problem, two-stage (acid and alkali catalyzed) method was used for biodiesel synthesis. More than 90% ester was obtained when two-stage method was used compared to 50% ester in single stage alkaline catalyst. In the case of mixed alcohol, a relatively smaller amount of ethyl esters was formed along with methyl esters. Acid value, viscosity, and cetane number of all the esters prepared from WFG were within the range of the ASTM standard. Esters obtained from WFG showed good performance as a lubricity additive.

2.2 VEGETABLE OILS

Over the past 100 years, a wide range of alternative fuels had been employed in CI engines. Vegetable oils were first seriously considered as petroleum diesel replacement or examined. Various researchers have used different kinds of raw vegetable oils. Akor et al (1983) used raw palm oil in diesel engines and they found that high viscosity of raw oils caused problems with fuel atomization and fuel flow. They also noted lower efficiencies with palm oil compared to petroleum diesel. Pryde (1983) presented the advantages of both untreated and treated vegetable oils in DI engines and recommended that pre-chamber diesel engines are best suited for vegetable oils. Ali & Hanna (1994) reviewed the use of vegetable oils and animal fats
and strongly recommended transesterification for reducing the viscosity of vegetable oils.

Goering & Daughterty (1982) studied the characteristic properties of eleven vegetable oils to determine which oil would be best suited for use as an alternative fuel source. Of the eleven oils tested, corn, rapeseed, sesame, cottonseed, and soyabean oils had the most favorable fuel properties. Engine performance is influenced by basic differences between diesel fuel and the vegetable oils such as viscosity, density, molecular content and mass based heating values. Since the mass based heating values are lower for vegetable oils, larger flows are required to maintain the power of the engine.

Rao & Mohan (2003) investigated the performance of diesel engine with untreated cotton seed oil as the fuel under supercharged condition. They have studied the effect of the fuel injection pressure besides varying the boost pressure and felt that supercharging was mandatory when one intends to develop power close to diesel operation with untreated vegetable oil.

Forson et al (2004) used 50%, 20% and 2.6% of jatropha curcas oil with diesel fuel and investigated the effect of preheating. Increase in BTE, brake power and reduction in SFC were obtained by them. The 2.6% jatropha curcas oil blend produced maximum BTE and brake and they suggested that jatropha curcas oil can be used as an ignition accelerator additive for diesel fuel. Sharma et al (2005) studied the performance and emission characteristics of DI diesel engine using neem-diesel blends and they reported no starting difficulties and reduced exhaust emissions. Since the highest BTE and lowest BSFC were observed over entire load range they have recommended an optimum injection pressure of 160 kg/cm$^2$ for both diesel fuel and neem-diesel fuel blends.
Senthil Kumar et al (2001 a) converted a single cylinder diesel engine to use jatropha oil as the pilot fuel and methanol as the inducted primary fuel mode and observed reduced smoke levels and increased HC and CO emissions. Ziejewski et al (1995) tested 25% of raw sunflower and sunflower oils with diesel fuel and obtained low CO, CO₂, NOx and HC emissions for sunflower oil blend and low PAH level sunflower oil blend.

Short term performance test were conducted by Pryor (1983) to evaluate crude soyabean oil and crude-degummed soyabean oil as a complete substitute for diesel fuel. The vegetable oils were found to contain 94% to 95% of the energy content of diesel fuel, and approximately 15 times as viscous. There was no difference in the short term engine performance and the power output was the same, thermal efficiency was lower and exhaust temperature was significantly higher with soyabean oil as fuel blend. Niemi & Illikainen (1997) optimized the performance and exhaust emissions of a DI turbocharged tractor diesel engine by advancing the injection timing with mustard seed oil. The engine generated a brake torque equal to that achieved with diesel engine and the brake thermal efficiencies were rather similar, and the use of retarded injection timing further reduced NOx emissions. The exhaust smoke was lower at medium and high loads and the engine emitted considerably higher quantities of PM.

Peterson & Reece (1983) evaluated sunflower, safflower and rapeseed oils as possible sources for liquid fuels. Over 30 different vegetable oils have been used to operate CI engines since the 1990’s (Quick 1980). Initial engine performance suggested that these oil-based fuels have great potential as fuel substitutes. Extended operations indicated that carbonization of critical engine components resulted in the use of raw vegetable oil fuels, which can lead to premature engine failure. Blending vegetable oil fuels can lead to premature engine failure. Blending vegetable oil with diesel fuel was
found to be a method to reduce coking and extend engine life. Pramanik (2003) studied the performance of jatropha curcas oil-diesel blends in CI engine and reduced the raw oil viscosity by blending with diesel. Alternatively, the author preheated the raw oil to 70°C to get viscosity equal to that of diesel fuel and obtained acceptable BTE with 50% blend.

Bacon et al (1981) evaluated the use of several vegetable oils as potential fuel sources. Initial engine performance tests using vegetable oils were found to be acceptable, the use of these oils caused carbon build up in the combustion chamber. Continuous running of a diesel engine at par-load and mid-speeds was found to cause rapid carbon deposition rates on the injector tips. Therefore short two hour tests were used to visually compare the effects of using different vegetable oils instead of diesel fuel. Although short-term engine test results were promising, they recommended long-term engine testing to determine the overall effects of using vegetable oils as fuel substitutes in diesel engines.

Schoedder (1981) used rapeseed oil as a diesel fuel replacement in Germany. Short-term engine tests indicated that rapeseed oil had similar energy outputs when compared to diesel fuel. Initial long-term engine tests showed that difficulties arose in the engine operation after 100 hours due to deposits on piston rings, valves and injectors. The investigator indicated that further long-term testing was needed to determine if these difficulties could be averted.

Bruwer (1980) studied the use of sunflower seed oil as a renewable energy source. When a tractor was operated with 100% sunflower oil, an 8% power loss occurred after 1000 hours of operation. The power loss was corrected by replacing the fuel injectors and injectors pump to supply additional fuel. After 1300 hours of operation, the carbon deposits in the engine were reported to be equivalent to an engine fueled with 100% diesel
except for the injector tips, which exhibited excessive carbon build-up. Yarbrough et al (1981) and Engler et al (1983) tested sunflower oil as a replacement fuel for diesel in agriculture tractors. Engine performance using the sunflower oil was similar to that of diesel fuel, but there was a slight decrease in fuel economy. Oxidation of the sunflower oil left heavy gum and wax deposits on the test equipment, which could lead to engine failure. Raw sunflower oil was found to be an unsuitable fuel, while refined sunflower oil was found to be satisfactory. Degumming and de-waxing the vegetable oils were required to prevent engine failure even if the vegetable oils were blended with diesel fuel. Schlick et al (1986) used soyabean and sunflower oil in a 25% blend with petroleum diesel fuel. While the fuels performed satisfactorily, there were significant deposits on all combustion chamber parts at 200 hours operation.

2.3 LIMITATION OF VEGETABLE OILS

In general, most researchers concluded that the direct use of vegetable oils caused short-term problems like cold starting, plugging and gumming of filter lines.

The long term problems are engine oil contamination, stuck piston rings, and excessive carbon build-up on cylinder head, piston and injector tip due to incomplete combustion of fuels, poor fuel injector spray patterns and flow problems due to the very high viscosity, excessive wear and tear of engine and lubrication failure due to polymerization of blow by vegetable oil in crank case. Oil deterioration and incomplete combustion are severe problems associated with the use of vegetable oils. A simple processing of vegetable oils like basic filtration, degumming and preheating might not be sufficient to overcome the problems mentioned above.
2.4 BIODIESEL

The American Society for Testing and Material (ASTM) defines biodiesel fuel as mono alkyl esters of long-chain fatty acids derived from a renewable lipid feed stocks, such as vegetable oils or animal fats, for use in diesel engines (Senatore et al 2000, Rosca et al 2005). The definition of mono alkyl esters means that pure vegetable oils and mono and di-glycerides cannot be considered as biodiesel. Furthermore, the fact that biodiesel must be produced from renewable fats eliminates any confusion with other substances to which this name has been attributed in the past. Further specification regarding its general use in diesel engines differentiates it from other biofuels, such as ethanol or gasoline substitutes.

2.5 PERFORMANCE OF BIODIESEL-DIESEL BLENDS

Spataru & Roming (1995) analyzed power parameters including engine speed, torque, brake horse power and fuel flow rate with the soyabean methyl ester (SMF) – diesel blends and noticed only small variations (less than 1.5%) as the percentage of SMF was increased, which is shown in Table 2.1. The emission values for diesel and SMF-diesel fuel blends are shown in Table 2.2, which depicts that the increasing percentages of SME blended with diesel led to increased emissions of NOx and CO₂ and reductions in THC and CO.

<table>
<thead>
<tr>
<th>Test</th>
<th>Diesel</th>
<th>B20</th>
<th>B30</th>
<th>B40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Speed, rpm</td>
<td>2,003</td>
<td>2.003</td>
<td>2.003</td>
<td>2.003</td>
</tr>
<tr>
<td>Engine Power, kW</td>
<td>195</td>
<td>198</td>
<td>196</td>
<td>192</td>
</tr>
<tr>
<td>Engine Torque, N-m</td>
<td>928</td>
<td>946</td>
<td>933</td>
<td>918</td>
</tr>
<tr>
<td>Fuel Flow, kg/h</td>
<td>47.8</td>
<td>49.4</td>
<td>49.3</td>
<td>49.0</td>
</tr>
</tbody>
</table>
Table 2.2  Comparison of exhaust emissions from SME/diesel blends (g/bhp-h)

<table>
<thead>
<tr>
<th>Fuel Blend</th>
<th>Total PM</th>
<th>THC</th>
<th>NOx</th>
<th>CO</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>0.257</td>
<td>0.57</td>
<td>4.43</td>
<td>1.22</td>
<td>671</td>
</tr>
<tr>
<td>B20</td>
<td>0.270</td>
<td>0.48</td>
<td>4.70</td>
<td>1.12</td>
<td>688</td>
</tr>
<tr>
<td>B30</td>
<td>0.258</td>
<td>0.42</td>
<td>4.78</td>
<td>1.03</td>
<td>688</td>
</tr>
<tr>
<td>B40</td>
<td>0.258</td>
<td>0.38</td>
<td>4.89</td>
<td>0.95</td>
<td>686</td>
</tr>
</tbody>
</table>

Krahl et al (1996) reviewed the utilization of rapeseed oil, rapeseed methyl ester (RME) and diesel fuel in terms of exhaust gas emission and they were of the opinion that more stress should be given to RME than rapeseed oil alone. Rao & Gopalakrishnan (1991) reported the results of tests conducted on DI engine with karanja oil, rice bran oil, palm oil and also with their corresponding methyl esters. They have recommended the use of methyl esters of vegetable oils rather than straight vegetable oils.

Rakopoulos et al (2005) conducted an experimental study with olive oil in DI and IDI engines. They have used 25:75 and 50:50 blends of olive oil and diesel fuel and observed slightly increased SFC, unaltered maximum pressures and moderate increase in exhaust smoke. Agarwal & Das (2001) studied the performance of a single cylinder DI diesel engine with methyl esters of linseed oil and found that 20% blend of biodiesel and diesel gave the best performance amongst all blends. Rosca et al (2005) examined the fuel injection characteristics for a biodiesel type fuel from waste cooking oil and concluded that it is possible to use B50 or B100 type fuels for fuelling the diesel engine, if proper adjustments of the injection timing are made.

Senthil Kumar et al (2001) used JME as pilot fuel and orange oil as the inducted fuel in a dual fuel diesel engine and observed reduced smoke levels and improved thermal efficiency. Rao & Mohan (2005) carried out a performance evaluation of DI and IDI engines with JME. They concluded that
biodiesel operation with supercharging is the best technique for DI engines and biodiesel operation under natural condition in the case of IDI engines. Sharp et al (2005) observed 20% soy methyl ester-80% diesel blend (B20) reduced HC emission and small reductions in aldehydes and PAH.

Clark et al (1999) tested soyabean biodiesel in CI engine and suggested to consider timing changes, exhaust gas recirculation and variable geometry turbo charging to get a better performance from biodiesel fuels. Sirman et al (2000) tested B20 soyabean biodiesel in an advanced automotive diesel engine and observed the reduced PM emissions, HC, CO and NOx emissions. The authors suggested adjustment of engine parameters such as injection timing and exhaust gas recirculation levels for further reductions in emissions.

2.6 NEAT BIODIESEL

B100 or 100% biodiesel is seriously being considered as a fuel of choice by operators fuelling in environmentally sensitive areas (Rahmen & Phadatare 2004, Biswas et al 2005). Scholl and Sorenson (1993), Schumacher et al (1993) and Reece & Peterson (1995) reported reductions in smoke density when fuelling with biodiesel as compared to diesel. Reece used rapeseed derived biodiesel while Schumacher used soyabean derived biodiesel fuels. Rao & Gopalkrishnan (1991) however, noted increases in smoke density when operated with pure karanja baxed biodiesel. Scholl and Sorenson (1993) observed reductions in HC and CO with soyabean derived biodiesel. Reece & Peterson (1995) noticed reductions in power ranging from one to seven percent while Schumacher et al (1993) observed increased power (3%) using a Cummins 5.9L DI turbocharged engine. Increased power was also observed by Feldman & Peterson (1992) during a 200 hour test using a 3 cylinder, DI, naturally aspirated diesel engine with the injection timing advanced by 2 degrees. Shifting the timing appears to be an appropriate and
acceptable method that should be used to optimize the CI engine for biodiesel fuelling. Sharp et al (2005) tested a heavy-duty diesel engine with 100% soy biodiesel and observed a 10% increase in NOx, a 77% reduction in PM and a 25% reduction in CO. Schumacher et al (1996) observed that fuelling of CI engines on 100% soyabean methyl ester (SME) slightly reduced the power when compared to that fuelled with petroleum diesel fuel. The specific power developed by CI engine fuelled on 100% biodiesel will vary depending on the engine design and fuel delivery. CO, HC, PM and smoke exhaust emissions tend to be lower when fuelled with biodiesel, while NOx exhaust emissions tend to be higher. Materials from engine wear were found to be lower in the analysis of the engine lubricating oil (Fe, Pb, and Si).

However, it should be pointed out several studies dealing with the emission and performance characteristics of biodiesel fuels did not reach unequal results and different behaviors have often been registered depending on the engine type, on the operating and maintenance conditions, on the testing methods, on the injection system and on its calibration.

2.7 COMBUSTION CHARACTERISTICS OF RAW OIL AND BIODIESEL

Senthil Kumar et al (2006) explored the combustion characteristics of neat animal fat, animal fat emulsion with ethanol and water and compared them with diesel fuel. Figure 2.1 illustrates the peak pressure and Figure 2.2 illustrates the heat release pattern at maximum power output. They have observed that neat animal fat and its emulsion follow the same trend similar to diesel. It can be seen from Figure 2.2 that combustion is more pronounced at the diffusion phase rather than the premixed phase with neat fat. However, ethanol-animal fat emulsion indicates an improvement in heat release rate at the premixed combustion period. It clearly shows a delay at the starting position of heat release compared to that of diesel fuel and neat animal fat.
They have observed that although more fuel is needed for the emulsion to obtain the same power as compared to diesel, the increase in fraction of the premixed burning phase and shortening in diffusive burning phase could be still achieved with the emulsions.

![Variation of cylinder pressure with animal fat-ethanol emulsion](image)

**Figure 2.1 Variation of cylinder pressure with animal fat-ethanol emulsion (Senthil Kumar et al 2006)**

Scholl & Sorenson (1993) investigated the combustion and experimental measurements of performance, emissions and rate of heat release for different fuel injection timings with soyabean methyl ester (SME) in diesel engine. The initial combustion rates for the two fuels were almost identical. The diesel fuel had a slightly longer ignition delay, and also had a slightly higher maximum combustion rate during the premixed stage of combustion. There were no distinguishable differences in the combustion rate of the two fuels once the premixed combustion is completed.

Grimaldi et al (2002) calculated the heat release rate for rapeseed methyl ester (RME) and they observed higher biodiesel combustion rate.
They concluded that because of 12% lower heating value of RME diesel, a higher mass was required to obtain the same energy release. The higher biodiesel burning rate was undoubtedly responsible for its higher Nox emissions, although, on the other hand, it contributed to the reduction of soot formation.

Figure 2.2 Variation of heat release rate with animal fat-ethanol emulsion (Senthil Kumar et al 2006)

Tsolakis et al (2007) studied the engine performance and emissions of a diesel engine operated on diesel-RME blends. Figure 2.3 shows the effect of fuel blend composition on the cylinder pressure and net heat release rate (NHRR) at IMEP of 4.5 bar and 6.1 bar. The authors observed that the increase of RME percentage in the fuel blend in the premixed phase and shift the start if combustion to an early stage and hence increased the in-cylinder pressure compared to petroleum diesel combustion. Biodiesel such as RME is less compressible than diesel fuel, so the pressure in the pump-line-nozzle type fuel injection system can develop faster, and pressure waves can propagate faster in biodiesel than diesel even at the same nominal pump
timing. As a result, the injection of biodiesel fuel started earlier with higher pressure and rate and at the same CA degree, the mass of biodiesel injected it higher than the corresponding mass of diesel. The increased viscosity of RME led to reduce fuel losses during the injection process, which led to a faster evolution of pressure and thus, advanced injection timing (Choi et al 1997). The combustion of the increased injection pressure and similar cetane number of RME compared to diesel result in an increased amount of fuel undergoing premixed combustion at an early stage. The higher density of RME in conjunction with the increased injection pressure results in the delivery of a higher amount of fuel at the same injection setting conditions. Combustion, therefore, takes place over a shorter period of time, and this possibly allows less time for cooling by heat transfer and dilution. It results in a higher NO\textsubscript{X} formation associated with the combustion of RME.

![Figure 2.3 Effects of fuel blend composition on the cylinder pressure and NHRR at IMEP 4.5 and 6.1 bar (Tsolakis et al 2007)](image)

2.8 ENGINE OIL ANALYSIS

Darcy et al (1983) used processed cotton seed and sunflower oil and 25\% crude sunflower-diesel blend in CI engine. They observed that lubrication oil contamination as evidenced by the percentage of total solids
was the greatest for 25% crude sunflower oil. Boron and sodium were elements which may indicate coolant leakage to lubricating oil. Total solid accumulations in lubricating oil were lower with cotton seed oil fuel than with diesel or sunflower oil. Taberskai et al (1999) performed an engine tear down analysis and found the presence of wear metals in the lubricating oil when biodiesel was used. They have reported the reduced lubricating oil viscosity due to the fuel dilution coming from the injector pump.

2.9 BIODIESEL AND ITS BENEFITS

Biodiesel has the following advantages over raw vegetable oils as an alternative diesel fuel:

- Biodiesel can be blended with diesel fuel in any proportion and it can be used in conventional diesel engine without any major modification


- Biodiesel is nontoxic and biodegradable when introduced in neat form (Zang et al 1998, Sharp et al 2000)

- Since biodiesel is an oxygenated fuel, it contributes to a more complete fuel burn (Rakopoulos 1992, Bertoli et al 1997, McCormick et al 2000)

- Cetane number of biodiesel is higher than that of vegetable oil and diesel fuel (Hansen & Jasen 1997, Zhang et al 1998, Grimaldi et al 2002) and hence produces less THC emission

Since biodiesel can be used in conventional diesel engines, the renewable fuel can directly replace petroleum products by reducing the country’s dependence on imported oil

Biodiesel offers safety benefits over petroleum diesel because it is much less combustible, with a flash point greater than 150°C, compared to 64°C for petroleum diesel. It is safe to handle, store and transport (Richard & Thompson 1993)

Inorganic makeup of bio-derived oils may work as an inherent additive for particulate trap regeneration (Zabetta et al 2006)

Erosion control in the production areas can be achieved by planting of perennial tree crops


Use of biodiesel results in low carbon build up and low smoke emission (Murayama 1984, Kaufman & Ziejewski 1984, Agarwal 2007)
2.10 LIMITATIONS OF BIODIESEL

The drawbacks of biodiesel in diesel engine operation are:

- Slight decrease in fuel economy on energy basis (about 10% for pure biodiesel operation)
- Increase in NO\textsubscript{X} emissions in most cases (Sinha & Agarwal 2005 a, Richard & Thompson 1993, Kinoshita et al 2003, Choi et al 1997, Spataru & Roming 1995)
- Thickens more than diesel fuel in cold weather, and it may need to use blends in sub – freezing conditions (Chang & Gerpen 1998)
- Pour points and cloud points are much higher than that of diesel fuels, which can cause filter plugging and operational difficulties in cold climates (Bari 2002 a, Shudo et al 2005)

2.11 EFFECTS OF BIODIESEL ON HEALTH AND ENVIRONMENT

2.11.1 Human Exposure Risks and Health Effects of Biodiesel

The toxicity to humans who have ingested or who have been dermally exposed to biodiesel was tested by Reece & Peterson (1993). The authors looked at acute oral and dermal toxicity and acute aquatic toxicity of RME and REE biodiesel fuels and their blend with diesel. In general, the authors reported that the occurrence of clinical observations increased as the ratio of diesel fuel in the blend being tested increased. 20% RME was the least severe in the acute oral toxicity study and the 100% REE was the least severe. It was found to be not as toxic as the reference toxicant, sodium chloride, but diesel fuel was 2.6 times more toxic.
2.11.2 Mutagenic Effect of Biodiesel

Krahl et al (2003) investigated the influence of RME, low sulphur diesel and petroleum diesel fuel on health effects. The mutagenic effects of the particle extracted from the fuels tested showed very strong variation and RME produced the lowest mutagenic effects. The very small number of mutations for RME is ascribed to a lower content of polycyclic aromatic compounds (PAC) in particle emissions of biodiesel fuels (Perkins et al 1991). Similar studies were carried out by Rantanen et al (1993), Bagley et al (1998), Krahl et al (2009) and Knothe (2010) and they have concluded that the number of particle was reduced with biodiesel fuels.

2.11.3 GNG Emissions and Ecological Effects of Biodiesel

Increased CO₂ in the atmosphere can cause global warming by allowing solar radiation to reach the earth, but restricts infrared radiation from escaping back into space. Combustion of fossil fuels, which comprised ancient carbon, in a relatively short period of time increases the accumulation of carbon in the atmosphere, eventually leading to global warming. Peterson & Hustrulid (1998) conducted a carbon cycle study of rapeseed biodiesel fuel as compared to petroleum diesel. The authors proposed that any substitution of biodiesel for petroleum diesel will ultimately slow the accumulation of atmospheric carbon. The basis for this proposal is that the carbon released from combustion of the biomass fuel will be extracted by the oil producing plant, thus saving nearly an equivalent amount of ancient carbon from accumulating in the atmosphere.

Gibbs (1998) reported on the need for carbon reduction technologies to offset carbon emissions from petroleum fuel use. The Kyoto Protocol required CO₂ reduction of 8% over 1990 levels for participating industrialized
nations, but the prospect seems grim given the current trends. The tremendous increase in the number of vehicles produced has the potential of increasing the atmospheric carbon levels by nearly one Gigaton every 15 to 20 years. Biomass fuels offer considerable promise for reducing or stopping additional carbon release in the atmosphere by recycling atmospheric CO$_2$. Franke & Reinhardt (1998) performed a life cycle analysis of biodiesel fuel use and interpreted the environmental impacts. They concluded that RME can have an overall ecological advantage as compared to diesel fuel, based on CO$_2$ balance, NO$_X$, SO$_2$, N$_2$O, PAH, dioxins and furans.

2.11.4 Unregulated Emissions from Biodiesel

Sharp et al (2000) studied the effect of soyabean methyl ester fuel on modern diesel engines. The use of 100% soyabean methyl ester results in dramatic reductions in both engine-out and catalyst-out PAH emissions. The large reductions in PAH are not unexpected when considering that biodiesel contains no aromatics, and no PAH compounds. The engine-out nitro-PAH compounds showed even larger reduction with biodiesel than the PAH compounds.

Krahl et al (2003) investigated the influence of RME on the exhaust gas emissions using a Daimler Chrysler diesel engine. They observed very low PAH emissions, very low unsaturated HC like ethane, methane and propane, low aldehyde emission and low PM emission. McGill et al (2003) studied emission performance of RME and SME with a special emphasis on unregulated emissions in the 7.3 liter engine. There were for the lowest engine load cases and for the 1, 3 butadiene, even those differences were not apparent between the fuels tested.
2.11.5  Biodegradability of Biodiesel

The biodegradability of biodiesel in the aquatic environment using a CO$_2$ evolution method was examined by Zhang et al (1998). They concluded that biodiesel fuels are readily biodegradable when introduced in pure form and also appeared to co-metabolize fossil diesel fuel blends. Diesel degradation rates in a blend were increased to three times than that of diesel alone due to co-metabolism. It is reported by Rickard and Thompson (1993) that 98% of spilled rapeseed methyl ester is broken down within three weeks and the remainder within five weeks. Hence biodiesel may therefore find application in those niche markets where sensitivity to pollution can justify its substantial additional cost. In spite of the many advantages of biodiesel, higher NO$_X$ emission is one of the vital problems in using the same in diesel engines. Hence special focus is needed to analyze the problem further.

2.12  HIGHER NO$_X$ AND LOWER SMOKE EMISSIONS FROM BIODIESEL FUELS

The United States Environmental Protection Agency (EPA) produced a review of published biodiesel emission data for heavy-duty engines (McCormick & Christopher 2005). The results for NO$_X$, OM, CO, and HC emissions are summarized in Figure 2.4. The chart shows that, on an average, a substantial reduction in PM, CO, and HC can be obtained through the use of biodiesel. However, there is an increase in NO$_X$ emissions, by approximately 2% for B20 (20% biodiesel by volume) blend and 10% for B100 (near biodiesel) on an average. Engine model year and technology exhibited a large influence on NO$_X$ emissions with the change in NO$_X$ for B20 ranging from roughly + 8% to - 6%, but averaging +2%. The NO$_X$ emissions increase may limit the use of biodiesel in non-attainment areas and is therefore a significant barrier to market expansion for this new fuel.
Figure 2.4 Summary of United States EPA evaluation of biodiesel impacts on pollutant emissions for heavy-duty engines [note PM and CO curves overlap] (McCormick & Christopher 2005)

$\text{NO}_x$ is formed through high temperature oxidation of nitrogen ($N_2$) in the combustion chamber. The formation rate of $\text{NO}_x$ is primarily a function of combustion (flame) temperature, the resistance time of nitrogen at that temperature, and the contents of oxygen in the reaction regions in the combustion chamber. At high combustion (flame) temperatures, nitrogen ($N_2$) and oxygen ($O_2$) in the combustion chamber disassociate into their atomic states and participate in a series of reactions. The three principal reactions producing thermal $\text{NO}_x$ are described in Zeldovitch mechanism (Zeldovitch et al 1947, Huang et al 2009).

\[
\begin{align*}
\text{N}_2 + \text{O} & \rightarrow \text{NO} + \text{N} \\
\text{N} + \text{O}_2 & \rightarrow \text{NO} + \text{O} \\
\text{N} + \text{OH} & \rightarrow \text{NO} + \text{N}
\end{align*}
\]
NO\textsubscript{X} is one of the main ingredients involved in the formation of ground level ozone, which can trigger serious respiratory problems. It contributes to formation of acid rain. NO\textsubscript{X} and sulphur dioxide react with other substances in the air to form acids which fall to earth as rain, fog or snow or dry particles. Acid rain damages buildings and historical monuments and causes lakes and streams to become acidic. One member of NO\textsubscript{X}, nitrous oxide, is a greenhouse gas. It accumulates in atmosphere with other GHGs causing gradual rise in earth’s temperature. Nitrate particles and nitrogen dioxide can block the transmission of light reducing visibility in urban areas (Suryawanshi & Deshpande 2005).

Biodiesel generally has a higher cetane rating than diesel fuel, and is widely acknowledged as reducing PM emissions but yielding higher NO\textsubscript{X} emissions (Scholl & Sorenson 1993, Clark 1999, Williams et al 2006, Lin & Lin 2006, Jindal et al 2010). Graboski et al (1996) reviewed a range of earlier biodiesel studies and conducted emission studies on a Detroit diesel series 60 engine using a blend of 34% diesel and a methyl soy ester with a cetane number of 56.4 and an oxygen content of 11% by weight. The EPA heavy-duty engine transient test (40 CFR, Part 86 Subpart N) was employed. PM emissions (cold and hot test composite) declined from 0.30 g/bhp-h on diesel to 0.10 g/bhp-h on pure biodiesel. However, NO\textsubscript{X}, emissions rose from 4.64 to 5.17 g/bhp-h.

McCormick & Christopher (2005) produced biodiesel from soyabean oil, canola oil, yellow grease, and beef tallow and tested it in two heavy-duty engines. The biodiesel fuels were tested neat and as 20% by volume blends with a 15 ppm sulphur petroleum-derived diesel fuel. Figures 2.5 and 2.6 show NO\textsubscript{X} and PM results for testing of B100 and B20, respectively. Both B100 and B20 produce reductions in PM that is
independent of biodiesel feedstock. NO\textsubscript{X} emissions increase significantly for B100 and the increase is evident for all biodiesel fuels but the effect of feedstock is much less pronounced.

Choi et al (1997) examined the combustion of diesel/biodiesel blends using a single cylinder Caterpillar 3400 engine with the capability of performing split injections. They too, observed the substantial reduction in PM and a slight increase in NO\textsubscript{X} emissions found by other workers. They also compared emissions from a blend of diesel and octadecene with the biodiesel blend. The octadecene was chosen to make the blend resemble the biodiesel but contained no oxygen. The octadecene did not offer the PM reduction benefits of biodiesel, thus suggesting that it is the oxygen content of the fuel that yields the desirable emission behaviour.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.5.png}
\caption{NO\textsubscript{X} and PM emission results for testing of B20 fuel in Cummins ISB (error bars = one standard deviation) (McCormick & Christopher 2005)}
\end{figure}
Figure 2.6 NO\textsubscript{X} and PM emission results for testing of B100 fuel in Cummins ISB (error bars = one standard deviation) (McCormick & Christopher 2005)

Sinha & Agarwal (2005 a) and Agarwal & Das (2001) carried out research on a four stroke, transportation DI diesel engine with blends of RME and diesel ranging from 5 to 50% ester in the blend. Higher NO\textsubscript{X} emissions were observed by them for all biodiesel blends compared to mineral diesel as shown in Figure 2.7. Smoke opacity for exhaust from different fuels is shown in Figure 2.8. It shows that the smoke opacity values for all biodiesel blends are lower than mineral diesel and smoke opacity decreases with an increase in biodiesel concentrations. This result suggests lower PM emissions from the biodiesel fuelled engine. The same trend of increased NO\textsubscript{X} and decreased smoke emissions were observed by Crookes (2006) for RME-diesel blends, which are shown in Figures 2.9 and 2.10 and by Agarwal & Das (2001) for linseed oil methyl ester in a single cylinder variable speed engine.
Figure 2.7 NO$_X$ emissions for different blends (Sinha & Agarwal 2005a)

Figure 2.8 Smoke number at full load (Sinha & Agarwal 2005a)
Figure 2.9  Comparison of NO$_X$ emissions variation with load and fuel type (Crookes 2006)

Figure 2.10  Comparison of Bosch smoke number variation with load and fuel type (Crookes 2006)
The summary of the report given by several researchers is shown in Table 2.3, which further strengthens the increased trend of NO\textsubscript{X} emissions from the engines fuelled with biodiesel.

**Table 2.3  Studies with various blends of diesel reported with higher NO\textsubscript{X} emissions**

<table>
<thead>
<tr>
<th>Author</th>
<th>Engine used</th>
<th>Fuel used</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munoz et al (2004)</td>
<td>Isuzu model 166430, IDI, 4-Cylinder, TC DE</td>
<td>Sunflower ME</td>
<td>Reduced HC, CO; High NO\textsubscript{X}</td>
</tr>
<tr>
<td>Nagaraja and Kumar (2004)</td>
<td>Single cylinder, 4-stroke, DI DE</td>
<td>Rice bran oil ME</td>
<td>B20 gives 2.5% higher BTE, less smoke, High NO\textsubscript{X}, and HC</td>
</tr>
<tr>
<td>Kinoshita et al (2004)</td>
<td>Single cylinder, 4-stroke DE</td>
<td>Palm ME, RME</td>
<td>Almost same BTE, HC and NO\textsubscript{X} are less for PME, and high for RME</td>
</tr>
<tr>
<td>Bhardwaj and Abraham (2008)</td>
<td>CRDI, 4-stroke, TC inter cooled DE</td>
<td>Pungamia ME</td>
<td>Lower CO, UBHC, PM and smoke; Slightly higher NO\textsubscript{X}</td>
</tr>
<tr>
<td>Karthikeyan and Mahalakshmi (2007)</td>
<td>Single cylinder, 4-stroke, DE-dual fuel mode</td>
<td>Turpentine oil- diesel</td>
<td>35% high CO, 45% high UBHC; at full load 21% high NO\textsubscript{X}</td>
</tr>
<tr>
<td>Sundaresan et al (2007)</td>
<td>Single cylinder, water cooled 4-stroke DE</td>
<td>Jatropha ME</td>
<td>Comparable BTE, less CO, HC and smoke; high NO\textsubscript{X}</td>
</tr>
<tr>
<td>Takayuki and Takaaki (2005)</td>
<td>Single cylinder, water cooled, 4-stroke DI DE; 411 cc</td>
<td>Rich bran ME</td>
<td>High BTE, 13% higher NO\textsubscript{X}, at full load; lower CO, THC and smoke at all loads</td>
</tr>
</tbody>
</table>
Table 2.3 (Continued)

<table>
<thead>
<tr>
<th>Author</th>
<th>Engine used</th>
<th>Fuel used</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senator et al (2000)</td>
<td>TC DI 4-stroke DE, 1929 cc, 68 kW</td>
<td>RME</td>
<td>Same power, higher NO\textsubscript{X}, lower smoke, and CO</td>
</tr>
<tr>
<td>Canakci (2007)</td>
<td>Jhon Deere 4276T, 4-cylinder, 4-stroke, DI medium swirl DE</td>
<td>Soybean ME</td>
<td>11.2% higher NO\textsubscript{X}, 0.5% higher CO\textsubscript{2}, reduction of 60% smoke, 42.5% HC, 18.4% CO</td>
</tr>
<tr>
<td>Postrioti et al (2003)</td>
<td>European passenger car engine, 1910 cc, 74 kW, TC with inter cooler, DI common rail</td>
<td>Soybean ME</td>
<td>High CO and NO\textsubscript{X}, low HC and smoke</td>
</tr>
<tr>
<td>Rakopoulos et al (2008)</td>
<td>Mercedes-Benz, mini bus diesel engine, 6 cylinder, TC after cooled</td>
<td>Cotton seed ME, Sunflower ME</td>
<td>Same BTE, similar performance, higher BSFC, high HC and NO\textsubscript{X}, low CO; Cotton seed ME better than Sunflower ME</td>
</tr>
<tr>
<td>Crookes et al (2006)</td>
<td>Ricardo E6, variable CR research engine, 12.78 kW @ 3000 rpm</td>
<td>RME</td>
<td>Lower smoke, higher NO\textsubscript{X}, 38% aldehyde and ketone reduction, lowest soot/carbon materials, lowest mutagenic effect</td>
</tr>
</tbody>
</table>
2.13 **NO$_X$ EMISSIONS REDUCTION TECHNOLOGIES**

Various techniques have been tested and employed for the reduction of NO$_X$ emissions in CI engines. It includes pilot injection, late injection, multiple injection techniques, water injection, EGR, adding oxygenates, use of additives and use of catalytic converters. Pilot injection delays the development of high temperature regions. NO$_X$ is reduced by controlling the temporal development of localized high temperature regions. At present catalytic converters are limited in their conversion efficiency for oxides of nitrogen. One of the simplest ways to reduce NO$_X$ emissions is by late injection of fuel into combustion chamber. Water injection is effective but also expensive and an additional tank is necessary for water. At temperature below 0°C the water needs to be protected against freezing. In addition to fuel injection system, a rust proof water injection system is also required (Schmidt and Gerpen 1996). Some of the methods used to reduce NO$_X$ emissions are discussed in this section.

**2.13.1 Using Additives**

NO$_X$ emissions can be reduced in diesel engines by blending of cetane improvers. McCormick and Christopher (2005) studied the effect of 2-ethyl hexyl nitrate (EHN) in Cummins ISB engine and DDC Series 60 engine with soybean biodiesel and compared it with diesel containing 15 ppm (BP15). The effects of EHN on emissions are shown in Figure 2.11 and 2.12 for both engines, respectively. The ISB engine was tested with B20+4000 ppm of EHN producing a cetane number increase of 10 units. In both cases, the addition of EHN had no significant effect on NO$_X$, confirming the cetane insensitivity of NO$_X$ emissions in engines. The cetane improver had no impact on emissions of other regulated pollutants.
Figure 2.11 Results for testing of soy B20 containing 4000 ppm of EHN in the Cummins ISB engine (error bars = one standard deviation) (McCormick & Christopher 2005)

Figure 2.12 Results for testing of soy B20 containing 5000 ppm of EHN in the DDC Series 60 engine (McCormick & Christopher 2005)
2.13.2 Using Water injection and Water Emulsion

The use of water along with diesel and its effect at reducing NO$_X$ emissions have been dealt with by Abu Zaid (2004), Lin & Wang (2004), and Lin & Lin (2006). Water may be added to fuel in any one of the following ways: (i) by injecting continuously into the air stream via a single point system or periodically through the intake valves via multi-point system Lin & Wang (2004), (ii) by injecting directly into the cylinder through a separate nozzle or introducing to fuel within the injection nozzle in the absence of fuel injection, (iii) by stratified fuel-water injection or (iv) through the preparation of stabilized water-in-ester emulsion (Lin & Lin 2006).

Hamasaki et al (2001) studied the effect of emulsified waste vegetable oil methyl ester with water on emission characteristics of a high-speed DI diesel engine. They have observed that an addition of 15% water with biodiesel on mass basis reduced NO$_X$ emissions by 18% with some reduction of smoke and 3% improvement in BSFC. Similar results were obtained by Kinoshita et al (2004) when rapeseed methyl was emulsified with 15% of water. On the other hand, the studies made by Yoshimoto et al (1999) showed in Figure 2.13. that there was a considerable reduction in NO$_X$ emissions when biodiesel obtained from flying oil emulsified with water at different volume ratio between 15% and 30%. Figure 2.15 shows the result of emulsified biodiesel with 30% (vol.) water addition. Even with 30% water addition rate no significant NO$_X$ emission reduction was obtained. It is important to note that the kinematic viscosity of emulsified biodiesel increased exponentially with the increase of water addition rate as shown in Figure 2.14. The phase separation problem exists even after a certain period and is depicted in Figure 2.15. However excess use of water over a long period is detrimental to the engine and leads to corrosion (Bekal & Babu 2008).
Figure 2.13  Engine performance with gas oil, biodiesel and their water emissions at different fuel injection timings (Yoshimoto et al 1999)

Figure 2.14  Kinematic viscosities of fuels at different water addition rates (Yoshimoto et al 1999)
2.14 ADDITION OF OXYGENATES

Recently to reduce NO\textsubscript{X} emissions and smoke density simultaneously, the addition of oxygenates like ethanol or methanol with biodiesel-diesel fuel blends was investigated by several authors. McCormic et al (2000) investigated several oxygenates, n-octanol (C8), decanoic acid (C12), methyl soy ester (C17) using a 6V-92TA DEC II engine. They found that all tested oxygenated produced a significant PM reduction in the range of 12 to 17%, while NO\textsubscript{X} emissions increased. Shi et al (2005) studied the use of oxygenates consisting of 20% ethanol with methyl soyate (denoted by BE) added in 15% (BE15) and 20% (BE20) with base diesel fuel. Due to the more complete combustion of ethanol, both BE15 and BE20 produced NO\textsubscript{X} emissions than that of B20 and base diesel fuel.

Hu Chen et al (2008) investigated engine performance and emission characteristics of soy methyl ester-ethanol-diesel blend fuels in Cummins-4B diesel engine. They observed 30% smoke reduction with E10B (ethanol-10%; biodiesel-5%; diesel-85%), 55% with E20 and 85% with E30B compared to
diesel at BMEP of 0.58 MPa. At full load, all the three fuels produced higher NO\textsubscript{X} emissions than diesel fuel. They observed that with E10B, the engine produced the highest NO\textsubscript{X} emissions of 10.7 g/kW-h as compared to 8.73 g/kW-h with diesel at full load.

Shi et al (2006) studied the emission characteristics of a tri-compound oxygenated diesel fuel blend (BE-diesel0 in a Cummins diesel engine with a blend ratio 5:20:75 (ethanol: methyl soyate: diesel) by volume. The results from the operation of diesel engine with BE-diesel showed a significant reduction of 30% PM emissions and 5.6% to 11.4% increase in NO\textsubscript{X} emissions at tested conditions.

The studies show increases in NO\textsubscript{X} emissions with oxygenates, while the study made by Hu Chen et al (2007), in which 10%, 20% and 30% ethanol is blended with 10% rapeseed biodiesel and diesel blend (E10B, E20B and E30B), showed that at full load ethanol addition reduced the NO\textsubscript{X} emissions. They have reported that with increasing ethanol in the blends, the ignition time is decreased. In fact, ethanol can suppress soot formation in fuel-rich regions.

Qi et al (2010) added methanol as an additive by volume percentage of 5% and 10% with biodiesel-diesel blends and they obtained similar NO\textsubscript{X} and HC emissions to that of biodiesel-diesel blends at full load. They concluded that the addition of higher oxygen content and high volatility methanol can be a promising technique for using biodiesel-diesel blend efficiently in diesel engines without any modifications in the engine.

Jha et al (2009) studied the emission characteristics of diesel-biodiesel-ethanol (DBE) fuel blends on one used engine and two new engines. The results with DBE showed a significant reduction in NO\textsubscript{X} emissions in the new engines with increased ethanol concentration, whereas with the used
engine under similar conditions, an increased NO\textsubscript{X} emissions profile was observed. All et al (1995) used 12 different blends of methyl tallowate, methyl soyate, ethanol, and diesel fuel in a Cummins N14-410 diesel engine and found that engine performance with these fuel blends did not differ to a great extent from that with diesel fuel. In their study, the same engine fuelled by a blend of 80% diesel, 13% methyl tallowate and 7% ethanol emitted minimum emissions. Rahimi et al (2009) investigated blending of ethanol with sunflower methyl ester-diesel fuel blend (diesterol) and observed reduced NO\textsubscript{X}, CO, HC and smoke emissions.

Cheng et al (2008) experimented with naturally aspirated diesel engine fuelled by methyl-biodiesel (produced from waste cooking oil) in the blended mode and fumigation mode. They observed reduced NO\textsubscript{X} emissions in the blended and fumigation modes. In the blended mode, the blend is injected into the engine cylinder and the two fuels combusted together, resulting in much less unburned methanol and hence showed significantly lower NO\textsubscript{X} emissions in the engine exhaust.

**2.15 EXHAUST GAS RECIRCULATION (EGR)**

Recently EGR has emerged as a necessary means to meet the United States Environmental Protection Agency (EPA) NO\textsubscript{X} regulations for heavy-duty diesel engines with the implementation of the 2004 regulations where NO\textsubscript{X} release is restricted to 2.5 g/bhp-h (Jacobs et al 2003). Many researchers like Lin Shi et al (2006), Peng et al (2008) and Miller Jothi et al (2008) studied the effects of EGR in diesel engines whereas only a few researchers explored the effects of EGR in diesel engines. Likewise, only a few researchers, namely Tsolakis & Megaritis (2004), Tsolakis et al (2007) and Rakopoulos et al (2008) have studied the effects of EGR in engines fuelled with biodiesel. Hot EGR, a low cost technique of exhaust gas recirculation can be effectively used to meet the stringent emission norms. Cooled EGR
method, even though effective, is expensive and difficult to implement (Pradeep & Sharma 2007). Kimura (1999) have reported serious difficulties in maintaining a gas cooler system with the respect to its cooling capacity, weight, etc., especially in higher load regions. A few of the practical difficulties faced in a cooled EGR system like corrosion of gas cooler, cooling capacity at higher load and extra weight are avoided by hot EGR. A typical layout of the experimental test rig with EGR is shown in Figure 2.16.

EGR routes exhaust gas from preceding engine combustion cycles into the combustion chamber in succeeding combustion cycles. Therefore, the initial composition of the succeeding cycle’s mixture contains concentrations of burned combustion products, i.e. residual. These products primarily include CO₂ and H₂O, and much smaller concentrations of carbon monoxide, nitric oxides, hydrocarbons, particulates, sulphur dioxides, sulfates, etc. As the concentrations of the exhaust species in the intake charge increase, the concentrations of oxygen also decrease.

2.16 EFFECTS OF EGR

EGR reduces oxygen concentration and peak combustion temperature, which result in reduced NOₓ level. On the other hand, EGR significantly increases smoke emission, fuel consumption and reduces thermal efficiency unless suitably optimized. In general, the introduction of EGR influences diesel engine combustion in three different ways: thermal, chemical and dilution. The thermal effect is related to the increase of inlet charge temperature that affects volumetric efficiency and leads to an increase in the charge specific heat capacity due to the presence of CO₂ and H₂O (Pirouzpanath et al 2007).
On the other hand, the chemical effect is related to the dissociation of species combustion while dilution is related to the reduction of O\textsubscript{2} availability.

Engine performance and emissions of a diesel engine operated with diesel-rapeseed methyl ester (RME) blends with EGR were investigated by Tsolakis & Megaritis (2004) and Tsolakis et al (2007). The inlet charge was kept as much as possible at the same temperature when using EGR, so that the effects of inlet charge temperature on the ignition delay and combustion process could be eliminated. The use of the ignition delay shifted the smart
end of combustion to later stages in the compression stroke and expansion stroke respectively. The authors observed that the use of EGR was more effective in the case of biodiesel blend combustion, compared to diesel combustion. The authors concluded that the main reasons for the higher NO$_X$ emissions reduction with the use of EGR in the case of biodiesel fuelling were (i) the increased CO$_2$ dilution as more CO$_2$ enters the combustion as part of the EGR compared to diesel, (ii) the lower relative air/fuel ratio with biodiesel compared to operation with diesel and (iii) the retardation of the already advanced combustion from the use of biodiesel. Ladommatos et al (1996) investigated the effects of exhaust gas recirculation on combustion and NOx emissions in a high – speed direct – injection diesel engine.

2.17 MAGNETIC FUEL CONDITIONER

Magnetic fuel conditioner is the ideal and immediate solution until such time that we could follow the more complete solution of (1) doing away with the production of two stroke engines, Govindasamy (2007) (2) total unleaded petrol with all the automobiles fitted with catalytic converters, Govindasamy (2007) (3) the entire population of vehicles – presently 37.67 million – becomes new.

The most important factor in the magnetic fuel conditioner is the magnetic field intensity and the collimation of the magnetic lines of flux (Algae-X International, 1661 Estero Blvd Fort Myers Beach, FL 33931, USA). The intensity of the magnetic field is far superior to that generated by regular permanent magnets and the collimation of the magnetic fields renders the magnetic lines of flux exactly parallel to each other at extremely high densities (to the order of millions of lines of flux per sq. cm.). These devices are external online installations without cutting or modifying the fuel pipes and the magnetic energy generated through the magnetic fuel conditioner is
rendered concentric and exactly perpendicular to the flow of the fuel which is shown in Govindsamy, (2007) Figure 2.17.

![Figure 2.17 Schematic diagram of magnetic fuel conditioner](image)

2.18 SUMMARY

From the review of literature from various studies the following conclusions were made:

- Transesterification is the effective way to reduce the viscosity of vegetable oil and its associated problems
- Biodiesel produces low exhaust PM emissions, sulphur dioxide and lower aromatic HC emissions
- Slightly higher NO\textsubscript{X} emissions were reported with biodiesel fuelled engines
- Out of various methods discussed above, addition of oxygenates, EGR and Magnetic Fuel Conditioner were found to be prominent in reducing NO\textsubscript{X} emissions