CHAPTER 2

2.1 INTRODUCTION

Generally, there are three categories of vegetable oils for use as fuel for compression ignition engines. They are: straight or pure vegetable oil, vegetable oil-diesel fuel blends, and esters of vegetable oils (biodiesel) -diesel fuel blends. In this chapter, a review is made of literatures on topics of synthesis of biodiesel, of uses of straight vegetable oil and of biodiesel in diesel engine.

2.2 USE OF STRAIGHT VEGETABLE OIL IN DIESEL ENGINE

Many researchers used straight vegetable oils as fuel in diesel engine to study their performance, combustion, and emission characteristics. Some of these efforts are summarised below.

Abu-Qudais et al. [31] evaluated the performance and emission characteristics on a four-stroke, single cylinder, water cooled, naturally aspirated, direct injection, variable compression ratio diesel engine. The engine was fueled with a non-petroleum shale oil with reference to the petroleum diesel fuel. The experiments were conducted at fixed injection timing of 20°bTDC, 18:1 compression ratio and 2000 rpm. They evaluated the important properties of shale oil such as specific gravity, kinematic viscosity, flash point, pour point and distillation temperature; and were found to be less than diesel fuel. Furthermore, the calorific value was higher than diesel fuel. They reported that the brake thermal efficiency (BTE) of the shale oil is higher than that of diesel fuel due to better combustion of the shale oil.

Al-Hasan [32] presented the results of investigations carried on single cylinder, variable-speed, indirect injection (IDI) diesel engine (type Lister 8/1) powered with Pistachia Palestine (PP) oil-diesel blends in different fraction. Flash point and higher heating value of pure PP oil were respectively, 32°C and 32,499 kJ/kg. This indicates that the oil is more flammable than diesel fuel. It was reported that addition of PP oil to the diesel fuel decreases both brake power (BP) and BTE; and increase in the specific fuel consumption (SFC). This is due to the lower heating value of the PP oil compared to that of diesel. There is a small change in SFC which was observed when
using the diesel fuel and PP oil-diesel blends. Therefore, these fuels liberate almost the same amount of energy required to produce a certain amount of power without any engine hardware modifications.

Machacon et al. [33] used unmodified diesel engine for the experiments. The experiments were carried out at various engine loads. They used coconut oil-diesel blends in various concentrations for the test. They reported that the smoke and NOx emissions were lowered with increase in the amount of the coconut oil in the blend.

Van der Walt and Hugo [34] investigated the use of sunflower oil in both direct injection (DI) and IDI diesel engines. No adverse effects were observed while operating an IDI diesel engine over a period of 2000 h. But, the loss of power was observed in direct injected engine. This could be due to severely coked fuel injectors, carbon deposits in combustion chamber, and stuck piston rings.

Karaosmanoglu et al. [35,36] used Pancar Motor E-108 direct injection CI engine for the tests. The engine was fueled with sunflower oil. They did not find any significant differences in the fuel consumption and power over a period of 50 h. and they also did not find any engine problems during the tests. Zaktax [37] conducted the performance and emission tests on the same engine using the blends of sunflower oil and diesel (20/80 v%). They reported that about 62% of the NOx emission was reduced for the fuel blend compared to the diesel fuel at low engine speeds, but the difference reduced with the increasing engine speed.

The other researchers [38-43] reported that preheating of the vegetable oil is one of the effective methods of reducing viscosity. It can be used without any engine hardware modifications for short-term engine operation.

Pugazhavadiivu and Jayachandran [44] used waste frying oil (WFO), a non edible vegetable oil as an alternate fuel for CI engine. Preheating process decreased the high viscosity of WFO. They evaluated the effect of temperature on viscosity of WFO. The results reveal that, with the use of WFO, the SEC and BTE were improved. The exhaust emission such as carbon monoxide (CO) and smoke were decreased considerably. The maximum decrease in smoke emission and CO emission is
observed when the oil temperature was maintained at 135°C compared to that of oil at 75°C.

Silvo *et al.* [45] used stationary generator CI engine to evaluate the emission and performance characteristics of pure refined palm oil. The test engine was used for supply of energy to villages in the Amazon basin. The palm oil was preheated to 50°C for first 50 hours of engine operation and to 100°C for next 300 hours of engine operation. They observed that the higher level of deposits when the engine was operated with palm oil at 50°C but the levels were acceptable when the oil was at 100°C. Performance of the generator increased for the preheated oil compared to the engine operation in ambient condition.

Canakci *et al.* [46] have analyzed the emission and combustion characteristics of preheated crude sunflower oil in 38.8 kW, four cylinder, four-stroke, naturally aspirated, indirect injection, CI engine. The tests were carried out at full load condition at 1000 rpm, 2000 rpm and 3000 rpm (24%, 47% and 71% of rated speed). The oil temperature was maintained constant (75°C) for each test. In this study, they found the similar combustion characteristics of preheated crude sunflower oil and diesel fuel for short-term engine operation. The curves of heat release and cylinder gas pressure for both preheated crude sunflower oil and diesel fuel were found to be similar to each other at all engine speeds tested. The SFC increased by 5%, while, at 2000 rpm, the maximum BTE for preheated crude sunflower oil increased by 1.06%. However, exhaust emissions such as unburned HC emission, CO emission, and smoke emission were less for preheated crude sunflower oil on an average of 34%, 2.05%, and 4.66%, respectively, but CO emission increased by 1.77%. The researchers observed that, for short-term test, use of preheated crude sunflower oil in an engine does not have any adverse effect on the engine performance and emissions.

Rakopoulos *et al.* [47] carried out experiments to evaluate the use of straight vegetable oils such as cotton seed oil, sunflower oil, and olive oil in the authors’ laboratory. They used DI, turbocharged, multi-cylinder, Mercedes-Benz OM366LA’ mini bus, diesel engine installed in the laboratory to study the performance and exhaust emissions of selected vegetable oils. Vegetable oils are blended with the petroleum diesel fuel in the proportions of 10% and 20% on volume basis. The series
of tests were carried out at two different speeds (1200 rpm and 1500 rpm), and at three loads (20%, 40% and 60% of the full load). They observed less smoke, and more NOx, CO, and HC emissions for all vegetable oil blends tested when compared with neat petroleum based diesel fuel. However, there is no significant change in BTE of the blends tested when compared to neat diesel fuel.

Makame et al. [48] used a 66 kW, four-stroke, four-cylinder, turbocharged, direct injection, diesel engine to investigate the performance, emission, and combustion characteristics of the blend containing croton oil, butanol, and diesel fuel. The samples investigated were 80% diesel-15% croton oil-5%butanol and 80% diesel-10% carton oil-10% butanol on volume basis. The series of tests were carried out at a constant speed of 3000 rpm (75% of the rated engine speed), and at five loads (0%, 25%, 50%, 75% and 100% of the rated load). They observed the improvement in the fuel properties of vegetable oil when it is blended with diesel fuel and butanol. There was an increase in specific energy consumption (SEC) of blends at higher engine loads when compared with neat diesel fuel. Increase in the amount of butanol in blend results in improved heat release rate and in-cylinder pressure when compared to that of neat diesel fuel. However, emissions like CO and smoke decreased for the blends at higher loads in comparison to diesel fuel, but NOx emissions of the blends were similar to that of the diesel fuel.

2.3 USE OF STRAIGHT VEGETABLE OIL FOR BIODIESEL PRODUCTION

2.3.1 Chemistry background

![Transesterification reaction](image)

Fig.2.1: Transesterification reaction
Biodiesel obtained through a chemical process is popularly known as ‘transesterification’ [49]. This is a well known chemical reaction in organic chemistry. The transesterification reaction is shown in Fig.2.1. Chemically the fats or vegetable oils consist of 90-98% triglycerides and small quantity of mono and diglycerides [50]. Three moles of fatty acids headed with one mole of glycerin is called as triglyceride [51]. When triglyceride (vegetable oil) is reacted with methyl alcohol in the presence of base catalyst, the methyl ester and glycerol is formed. The base catalyst may be potassium hydroxide or sodium hydroxide or sodium methoxide. The purpose behind the use of catalyst is to increase the speed of the chemical reaction. The purpose of transesterification is to separate the glycerol content from vegetable oils or animal fats to improve the fuel quality.

It has been reported by the researchers [52] that the transesterification reaction is used in the soap industries. The glycerin content is removed from the vegetable oils as it is required for manufacturing of soap.

All animal fats and vegetable oils consist of saturated and unsaturated fatty acids. Lauric acid (C₁₂:0), Myristic acid (C₁₄:0), Palmitic acid (C₁₆:0), Stearic acid C₁₈:0), Arachidic acid (C₂₀:0), Behenic acid (C₂₂:₀), Oleic acid (C₁₈:1), Linoleic acid (C₁₈:2) and Linolenic acid (C₁₈:3) are the commonly present acids in vegetable oils at different percentages. If the fatty acid chains have no double bounds they are said to be saturated [53]. The vegetable oils such as coconut oil and palm oil contain saturated fatty acids, about 35% to 40%, and are in solid form at room temperature. Biodiesel production from such oils may result in gel formation at higher temperatures. Therefore these conditions should be avoided [54]. The molecular weight of triglycerides is in the range of 800 to 900 and is approximately four times larger than petroleum based diesel fuel. This could be the cause of vegetable oils to have low volatility. However unsaturated vegetable oils are inherently more reactive than diesel fuel. Therefore they are much more susceptible to oxidation and thermal polymerization reactions. Methyl esters from more saturated vegetable oils will have better oxidation stability and higher cetane numbers, but they have poor cold flow properties. The cold flow property may be improved with the use of anti gelling additives. However methyl esters with higher level of unsaturated fats will have poor
oxidation stability and lower cetane numbers, but they have better cold flow properties. [55,56].

Mohibbe Azam et al. [15] examined fatty acid profile of 75 plant seed oils having more than 30% fixed oil in their kernel or seed. They determined various parameters of methyl esters such as iodine value, saponification number and cetane number, and found them to be in the range of 4.8 to 212, 169.2 to 312.5, and 20.56 to 67.47, respectively. These parameters were used to predict the quality of biodiesel. Biodiesel of 26 species were found to meet the important specification of biodiesel. Generally, fatty acid methyl esters with higher cetane number are favored for use as biodiesel. However, with increase of cetane number, iodine value decreases which means that the degree of saturation increases. This will lead to the solidification of biodiesel at higher temperature. Therefore, to avoid this condition, the maximum limit of cetane number (65) has been specified in (ASTMPS 454-99) biodiesel Standard. However, the minimum value for cetane number is 47 as it is specified in ASTM D6751-02 biodiesel Standard.

2.3.2 Use of different feedstocks for biodiesel production

The utilization of different feedstocks for biodiesel production was studied by several researchers and is illustrated below.

During the synthesis of rapeseed oil ethyl ester, no separation of layer was observed by the researchers [57] when alcohol to oil molar ratio was 5.1:1, 1.3 (wt %) potassium hydroxide, and reaction temperature of 70°C after 120 min of reaction. However, the higher ester yield was obtained only after 60 min of reaction with the use of sodium methoxide as a base catalyst.

Saravanan et al. [18] used mahua oil with an initial acid value of 28 mg KOH/g. to synthesize mahua oil methyl ester, mahua oil ethyl ester, and mahua oil butyl ester with the use of sulfuric acid as a catalyst. All the experiments were carried out at the boiling point of alcohols without stirring the reactants. They obtained the optimum yield of about 75% (mahua oil methyl ester), 85% (mahua oil ethyl ester) and 95% (mahua oil butyl ester) with 7:1 alcohol to oil molar ratio, 6% H₂SO₄ after 5 h. Finally
they concluded that 1-butanol is the better alcohol in the development of biodiesel using a single-step acid esterification.

Freedman et al. [58] reported that the acid catalyst becomes more effective than alkaline catalyst if the vegetable oils have acid value more than 2 mg KOH/g. The maximum ester is obtained from soybean oil at 30:1 alcohol to oil molar ratio, 1% H₂SO₄, at 60°C after 44 h of heating.

An attempt has been made by Sharma and Bhaskar Singh [59] to develop methyl ester from high FFA non-edible kusum oil. The initial FFA of kusum oil was found to be 10.66% which required both acid esterification and transesterification. The identified saturated fatty acid was 53.11% and unsaturated fatty acid was 39.47%. The optimized amount of methanol to oil molar ratio was found to be 10:1 and 8:1 for acid esterification and alkali transesterification, respectively. The amount of acid catalyst (sulfuric acid) and alkali catalyst (potassium hydroxide) used for the reactions are 1 (v %) and 0.7 (wt %), respectively. The reaction time of 60 min. for both acid esterification and alkali transesterification at 50°C was optimum for development of biodiesel.

Sivakumar et al. [60] used dairy milk scum oil as a raw material in the development of methyl ester. The total percentage of identified fatty acids in raw material by Gas Chromatography (GC) analysis was 98.72. Saturated and unsaturated fatty acids were 78.78% and 19.94%, respectively. The maximum ester yield reached 98.7% when 6:1 methanol to oil ratio, 1.2 (wt%) of KOH, 30 min of reaction time, and 75°C of reaction temperature at 350 rpm.

Das and Sahoo [61] developed biodiesel from filtered, non-edible, renewable feedstocks such as polanga, karanja, and jatropha oils by transesterification. The acid value of unrefined, filtered polanga,karanja, and jatropha oils is found to be 44, 5.06, and 3.8 mg KOH/g, respectively. Jatropha oil consists of 22% saturated fatty acids and 78% unsaturated fatty acids. Karanja oil consists of 19.15% saturated fatty acids and 70.7% unsaturated fatty acids. Polanga oil consists of 24.96% saturated fatty acids and 72.65% unsaturated fatty acids. A two stage transesterification is used for karanja and jatropha oil; and a three stage transesterification for polanga oil are used
to develop high acid value oils to its methyl esters. They obtained about 91% karanja, 93% jatropha, and 85% polanga methyl ester at the optimized condition.

Yi-Hung Chen et al. [62] investigated the feasibility of methyl ester development from microalgae oil. The acid value and kinematic viscosity of microalgae oil were found to be respectively, 0.13 mg KOH/g and 33.06 mm$^2$/s. Transesterification of the microalgae was carried out for 60 min using alcohol to microalgae oil molar ratio of 6:1, catalyst (KOH) amount 1(wt%) at a reaction temperature of 60°C. The microalgae biodiesel obtained was found to within the limits of biodiesel Standards.

Bello et al. [63] extracted the cashew nut oil by soxhlet extraction method. The oil was transesterified with methanol in the presence of sodium hydroxide. The physicochemical properties of oil, methyl ester and its various blends with diesel fuel were determined following the EN and ASTM protocols.

Xinhai Yu et al. [64] used pistacia chinensis oil to develop its methyl ester. They used CaO-CeO$_2$ as mixed oxide solid alkali catalyst for the transesterification reaction. The effects of transesterification reaction parameters such as alcohol/oil molar ratio and reaction temperature were studied in order to achieve maximum ester yield. The results obtained showed that CaO-CeO$_2$ mixed oxides have a better potential for use in the synthesis of large scale biodiesel.

Moser [65] used refined walnut oil, hazelnut oil, and peanut oil to convert their ester with the use of sodium methoxide as alkaline catalyst. Zhi-Long Xiu et al. [66] synthesized the biodiesel from soybean oil with the use of methanol and solid calcined sodium silicate in transesterification mechanism. Parette et al. [67] produced biodiesel from low grade feedstocks with the use of MnO (manganese oxide) and TiO$_2$ (Titanium oxide) as solid catalysts.

Canoira et al. [68] synthesized biodiesel from jojoba oil wax by transesterification process with the use of methyl alcohol. Encinar et al.[69] developed biodiesel from waste frying oil ethyl ester by transesterification reaction with the use of potassium methoxide, potassium hydroxide, sodium methoxide, and sodium hydroxide as catalysts.
Ma et al. [13] reported that the cost of the feedstocks selected for biodiesel synthesis is the major contributor in the total development cost of biodiesel which comes to about 60-75% of the total cost for biodiesel synthesis. Demirbas [70] reported that the cost of the feedstocks contributes about 80% of total cost for biodiesel synthesis.

Low cost feedstocks with low percentage FFA content were found to be an additional advantage in the development of biodiesel by a single step alkaline transesterification. This reduces the total cost of biodiesel to a considerable amount.

2.4 USES OF BIODIESEL IN DIESEL ENGINE

The major problems of current Indian petroleum-based diesel fuel are their high sulphur content and lower flash point. However the biodiesel has lower sulphur content, lower aromatics, higher flash point, and higher cetane number compared to those of petroleum based diesel fuel. Generally, about 57% increase in flash point, 8% increase in cetane number, and total elimination of sulphur content is reported for biodiesel [71].

Diesel engines emit considerable amount of emissions such as hydrocarbons, sulfur, carbon monoxide, oxides of nitrogen, particulate matter, and many poly-aromatic hydrocarbons which lead to environmental degradation. This demands the replacement of diesel fuel or at least its reduction in usage by mixing it with a clean fuel [72-74].

For replacing the petroleum based diesel fuel used in IC engines, fuels of bio origin like methyl esters, alcohols, and biogas provide a better solution to the two crises of ‘environmental degradation’ and ‘fossil fuel depletion’. Some of these alternate fuels require modification to bring about some important properties very close to those of conventional fuels, while others can be used directly [75].

Biodiesel can be used in diesel engines with any mixture with neat diesel fuel. It emits lesser exhaust emissions compared to that of neat diesel fuel [76].

A series of experiments were carried by Canakci and Alptekin [77] to characterize the important fuel properties of pure diesel, methyl esters, and their various blends. They developed biodiesel from canola, sunflower, cottonseed, soybean, and corn oils.
The methyl esters obtained were blended with diesel fuel to obtain B02, B05, B10, B20, B50, and B75 on volume basis, and then characterized. Characterization includes determination of the combustion properties of the blends such as flash point, kinematic viscosity, distillation temperatures, pour point, and density. The results showed that the fuel properties of the blends from B02 to B20 related to combustion were very close to those of pure diesel.

Kinematic viscosity is an important fuel property as it has influence on fuel droplet size, the penetration and the atomization quality. Therefore, it has an effect on the combustion quality [78-80]. High viscosity leads to increase in fuel droplet size, needs high energy to pump the fuel, poor fuel atomization, incomplete combustion and increases the engine deposits, while low viscosity can cause leakage in the fuel system [4,78].

Fuel density is one of the most important parameters that has direct effect on the engine performance. Many combustion characteristics such as heating value and cetane number are related to density [81]. This property influences the atomization efficiency of fuel [82]. On the other hand variation of density influences the power output of the engine. This could be due to variation in mass injected to the engine [83,84].

It is observed that the esters are less volatile than the petroleum based diesel fuel. Some residue was left from esters at 350°C, which may be the cause of coke deposits on fuel injectors in CI engines. However, the air temperature in CI engines is about 800°C after it is compressed inside the engine cylinder. Therefore, use of esters in CI engine as an alternate fuel should not be a problem [79].

Canakci et al. [85] observed no engine problems in engine parts when the diesel engine is blended with biodiesel up to 20%. They observed better results for the blend B20 and considerable decrease in exhaust emissions emitted from the diesel engine. An urban bus diesel engine was operated by Ramadhas et al. [86]. They reported that no significant problems were observed during the test on B20. Fuel consumption of the blend was found to be about 2-5% higher than that of high speed diesel fuel. Further no separation was observed for the blend B20 at atmospheric temperature over a period of 90 days.
Saravanan et al. [87] investigated the emission and performance characteristics of mahua methyl ester in a naturally aspirated, single cylinder, direct injection, air cooled, compression ignition engine. They found that the energy consumption of mahua methyl ester was approximately 3-5% higher than that of neat diesel fuel at full load. This could be due to high viscosity and lower heating value of mahua methyl ester compared to diesel fuel. Therefore it requires larger storage space which might be a disadvantage for automotive applications. But this can be offset by an increase in the fuel injection pressure in order to increase the specific output of the engine [88,89]. Exhaust emissions such as NOx, unburned HC, and CO, were found to be lesser for mahua methyl ester compared to those of diesel fuel by 4%, 26%, and 20% respectively, at full load.

Raheman and Ghadge [90] evaluated the performance and emission characteristics of mahua methyl ester - diesel blends in a Ricardo E6 engine together with fuel property analysis. The tested fuel properties of mahua methyl ester were found to be within the limits of ASTM D 6750-02 and EN 14214 Standards. They reported that SFC of blends was high when compared with that of diesel fuel. It increased with an increase in the concentration of methyl ester in the blend. However, the BTE decreased with increase in the concentration of methyl ester in the blend. This could be due to the lower heating value of the methyl ester compared to that of diesel fuel. The maximum BTE for B20 and B40 were found to be 25% and 24%, respectively, as compared to 24% for diesel fuel at full load. This could be due to presence of oxygen content in the methyl ester which might encourage combustion in an engine. The exhaust gas temperature was found to higher for biodiesel-diesel blends. The EGT from B20, B40, B60, B80 and B100 was found to be respectively, 6%, 10%, 12%, 14%, and 16% higher than that of diesel fuel. Higher heat loss of the higher blends might be the reason for lower BTE when compared to diesel fuel. Exhaust emissions such as CO and smoke level decreased, whereas NOx increased with increase in the addition of methyl ester in the blend. However, the emissions level increased with increase in engine load for all the tested blends.

Dorado et al. [91] used olive oil methyl ester as alternate fuel for direct injection, CI engine. They reported that the test exhaust emissions like sulphur dioxide, oxides
of nitrogen, CO, and CO₂ emissions reduced by 57%, 32%, 59%, and 8.6%, respectively.

Raheman and Phadatare [92] used pongamia biodiesel-diesel fuel blends to study their performance and emissions in CI engine. They found decrease in emissions together with increase in brake power, torque, BTE, and decrease in fuel consumption.

Hazar [93] analyzed performance and emission characteristics on a four-stroke, single cylinder, air cooled, naturally aspirated, 6LD 400 Lombardini model stationary diesel engine. The engine was fueled with canola methyl ester–diesel blends in various concentrations. The experiments were conducted in both coated (piston surface, valves, and cylinder head of a CI engine were coated with ceramic materials) and uncoated engines. The tests were conducted at five different engine speeds (1800, 2100, 2400, 2700, and 3000 rpm) at full load conditions. An increase in engine power and decrease in SFC, as well as significant improvements in smoke density and exhaust emissions were observed for all the fuels tested used in the coated engine compared with the case of the uncoated engine. This could be due to low heat loss in coated engine leads improvement in combustion.

Gattamaneni et al. [94] produced biodiesel from rice bran oil by transesterification process meeting with ASTM D6751-02 and EN14214 biodiesel Standards. An attempt has been made to investigate the possibility of a partial replacement of rice bran biodiesel as a diesel engine fuel by evaluating the different concentration of biodiesel-diesel blends. Therefore, they evaluated the combustion and emission characteristics on a naturally aspirated, single cylinder, direct injection, air cooled, 4.4 kW stationary CI engine using rice bran methyl ester and its diesel blends as alternative fuel. The ignition delay and peak heat release for biodiesel and its diesel blends was found to be lower than that of diesel fuel. Addition of rice bran oil methyl ester in the blend decreases the ignition delay. The BTE of the methyl ester and its diesel blends are lower (about 1%) than that of diesel fuel at all loads. The exhaust emission such as unburned HC emission, CO emission, and soot concentrations were decreased with increase in the biodiesel concentration in the blend. The NOx emission
is increased with increase in the biodiesel concentration in the blend and is slightly higher than that of diesel fuel.

Rao et al. [95] produced jatropha methyl ester by transesterification meeting with ASTM biodiesel Standards. They used KOH as an alkaline catalyst in the reaction to increase the speed of the reaction. They evaluated the performance, combustion, and emission characteristics of the methyl ester, diesel and their blends on a naturally aspirated, single cylinder, air cooled, direct injection, 4.4 kW constant speed diesel engine. They observed that the ignition delay and peak heat release rate for jatropha oil methyl ester and its diesel blends are lower than those for diesel fuel. The addition of jatropha oil methyl ester in the blend decreases the ignition delay due to the inherent oxygen content of jatropha oil methyl ester. The peak cylinder gas pressure increases with an increase in load for all the blends tested. This could be due to increase in the amount of fuel injected at higher loads. The maximum heat release rate for the blend B100 and B80 occurs approximately 6° crank angle (CA) bTDC and for the other blends at 5° CA bTDC at full load conditions. At full load conditions the exhaust emission such as unburned HC emission, CO emission, and soot concentrations were decreased with increase in the biodiesel concentration in the blend. The NOx emission is increased with increase in the biodiesel concentration in the blend and is slightly higher than that of diesel fuel.

Canakci and Ozsezen [96] carried out the experiments to study the exhaust emissions of waste frying palm oil methyl ester and its blends with petroleum based diesel fuel in various percentages (B00, B05, B20, B50 and B100) on diesel engine. They used multi-cylinder (38.8 kW at 4250 rpm), IDI, turbocharged engine for the experiment. Engine tests were carried out over the different engine speeds of 1000, 1500, 2000, 2500, and 3000 rpm at full load condition. They discussed the relationships between the various fuel properties and the fuel line pressure, ignition delay, air-fuel equivalence ratio, and start of injection timing (SOI) to explain their effects on the exhaust emissions. The results obtained showed that when the test engine was fueled with biodiesel, ignition delay and air-fuel equivalence ratio decreased while the fuel line pressure increased. These behaviors lead to reduction in CO emission by about 57%, about 22% in smoke opacity, about 40% unburned HC
emissions when compared with petroleum based diesel fuel. However, it had the reversed trend on NOx emissions for all engine speeds.

Chang et al. [97] used blends of soybean oil isopropyl ester-diesel fuel and soybean bean oil methyl ester-diesel fuel in a turbocharged, four-cylinder John Deer engine. They observed significant decrease in particulate matter, CO emission and unburned HC emissions. However, about 12% NOx emission increased.

Wang et al. [98] studied the operation of the truck engine fueled with biodiesel and its blends with diesel fuel. They observed that the blend containing 35% biodiesel (B35) emitted lesser CO emission, particulate matter, and hydrocarbon emissions compared to neat diesel fuel. However, the NOx emission from diesel fuel and B35 were found to be in the same level.

Zhang and Van Gerpen [99] used turbo-charged, direct injection, four-cylinder, compression ignition engine modified with medium swirl type and bowl in piston. They observed shorter ignition delay and similar combustion characteristics as diesel fuel while using soybean oil biodiesel-diesel fuel blends as alternate fuel.

Ali et al. [100] used Cummins turbocharged, six-cylinder, 522 kW, DI, CI engine. The results showed that there was decrease in CO emission and no change in unburned HC emission and CO$_2$ emission. The smoke and NOx emissions were on par with diesel fuel. The better performance and lesser exhaust emissions were obtained for diesel fuel-methyl tallowate-ethanol (80-13-7) blend.

Pradeep and Sharma [101] studied the performance, combustion, and emission characteristics of rubber seed oil biodiesel-diesel fuel blends in diesel engine. Lesser brake thermal efficiency, lesser heat release rate, and higher combustion duration for the blends compared to diesel fuel was reported for biodiesel.

Singh and Singh [14] reported that biodiesel has become better alternate fuel for CI engines because it is made from renewable resources and because of its environmental benefits. Many methods are available for synthesis of biodiesel, but transesterification of fats or vegetable oils is the present method of choice. Researchers concentrated mainly on the non-edible oils in the syntheses of biodiesel. For the synthesis of biodiesel, an alkaline catalyst process has been established that
gives higher conversion efficiency. The recovery of glycerol is another way to reduce production cost.

Very few kinds of vegetable oil have been tested on CI engines and reported in literature. Among them many are edible type vegetable oil. The use of edible oil in engine increases the problem of adequate production of animal and human food. Certainly this increases the cost of edible oils as well as a shortfall in proteinous food. In India, so far the biodiesel is used for limited applications; mainly jatropha and pongamia biodiesels are used to run some railways and buses. Hence, there is a need to identify new kinds of non-edible vegetable oils and the need of the hour is to examine their suitability as an alternate fuel.

In the present work three kinds of non-edible vegetable oil viz. simarouba oil, mahua oil, and waste cooking oil for investigation in diesel engine. Among them simarouba oil and mahua oil, which have been not tested so far as an alternate fuel in multi-cylinder diesel engine as per knowledge of the author.

Therefore, the main objective of this work is to produce the methyl esters from three different types of vegetable oils meeting with the specifications of biodiesel Standards, and investigate the performance, combustion, and emission characteristics of the produced methyl esters and their various blends with diesel fuel on CI engine. To achieve the objective, experimental investigations were carried out using unmodified, four-stroke, four-cylinder, direct-injection, water-cooled, and naturally aspirated CI engine.