Chapter 2

Review of Literature

This chapter is devoted to a comprehensive review of the open research literature available on the development of a compression ignition engine using diesel as fuel and its subsequent application using esterified form of renewable biofuels popularly known as biodiesels. This review begins, as given in Section 2.1, by throwing some light on the history of development of diesel engines. Section 2.2 gives a review on recent studies in the field of biodiesels. The studies carried out by noted investigators are classified based on the nature of research conducted and is presented in Section 2.3. This review is separated into sub-sections. Section 2.3.1 deals with an exhaustive review of studies conducted on performance and emissions characteristics of different biodiesels. Studies related to combustion analysis using biodiesels are reviewed in Section 2.3.2. Computational studies are separately reviewed in Section 2.4 which includes studies related to multi-objective optimization and artificial neural network is dealt in Sections 2.4.1 and 2.4.2 respectively. Based on the review, the objectives of the present study are identified and are given in Section 2.5.

2.1 History of Diesel Engines

On February 27, 1892, Rudolph Diesel filed for a patent at the Imperial Patent Office in Germany. Within a year, he was granted Patent No. 67207 for a "Working Method and Design for Combustion Engines . . .A New Efficient, Thermal Engine." With contracts from Frederick Krupp and other machine manufacturers, Diesel began experimenting and building working models of his engine. In 1893, the first model ran under its own power with 26% efficiency, remarkably more than double the efficiency of the steam engines of his day. Finally, in February of 1897, he ran the first diesel engine suitable for practical use, which operated at an unbelievable efficiency of 75% (Plate 2.1).

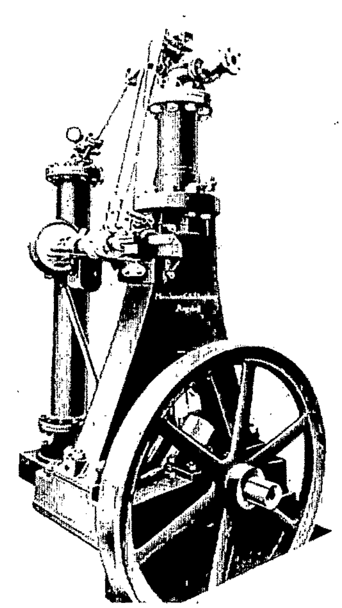

Plate 2.1 First Diesel Engine

Plate 2.2 Rudolph Diesel

Rudolf Diesel (A photograph of Rudolf Diesel is given in Plate 2.2) demonstrated his engine at the Exhibition Fair in Paris, France in 1898 (**K.C. Pandey [1]**). This engine stood as an example of Diesel's vision because it was fuelled by peanut oil - the "original" biodiesel. He thought that the utilization of a biomass fuel was the real future of his engine. He hoped that it would provide a way for the smaller industries, farmers, and common folk a means of competing with the monopolizing industries, which controlled all energy production at that time, as well as serve as an alternative for the inefficient fuel consumption of the steam engine. As a result of Diesel's vision, compression ignited engines were powered by a biomass fuel, vegetable oil, until the 1920's and are being powered again, today, by biodiesel.

The early diesel engines were not small enough or light enough for anything but stationary use due to the size of the fuel injection pump. They were produced primarily for industrial and shipping in the early 1900's. Ships and submarines benefited greatly from the efficiency of this new engine, which was slowly beginning to gain popularity. The 1920's brought a new injection pump design, allowing the metering of fuel as it entered the engine without the need of pressurized air and its accompanying tank. The engine was now small enough to be mobile and utilized in vehicles. 1923-1924 saw the first Lorries built and shown at the Berlin Motor Fair. In 1936, Mercedes Benz built the first automobile with a diesel engine - Type 260D.

Meanwhile, America was developing a diesel industry. It had always been part of Diesel's vision that America would be a good place to use his engines. Size, need, and the access to biomass for fuel were important for invention and were a part of the existing American scene. Adolphus Busch acquired the rights to the American production of the diesel engine. Busch-Zulger Brothers Diesel Engine Company built the first diesel engine in America in 1898. But, not much was done with development and design of the engine here until after World War I.

Clessie L Cummins, a mechanic-inventor who had been set up in business in 1919 by the investment banker William Glanton Irwin, purchased manufacturing rights to the diesel engine from the Dutch licensor Hvid. He immediately began working on the problems, which had been inherent in the engine since its inception - those of size, weight, and instability created by the fuel system. Cummins soon developed a single disk system that measured the fuel injected. Like the other early engines, Cummins' products were stationary engines and his main market was the marine industry.

It was also during the 1920's that diesel engine manufacturers created a major challenge for the bio fuel industry. Diesel engines were altered to utilize the lower viscosity of the fossil fuel residue rather than a biomass based fuel. The petroleum industries were growing and establishing themselves during this period. Their business tactics and the wealth that many of these "oil tycoons" already possessed greatly influenced the development of all engines and machinery. The alteration was first step in the elimination of the production structure for biomass fuels and its competition as well as the first step in forcing the concept of the biomass as a potential fuel base into obscurity, erasing the possibilities from the public awareness.

1929 and the Stock Market crash brought the threat of bankruptcy to Cummins. In an innovative move, he installed a diesel engine in a limousine and took his backer, Irwin, for a ride, assuring further investment. Cummins continued to experiment with the diesel vehicles, setting a speed record in a Duesenberg at Daytona, driving a truck with a Cummins diesel engine coast to coast on $11.22, and establishing an endurance record of 13,535 miles at Indianapolis Speedway in 1931. Cummins' diesel engines were established and trucks as well as other fleets began using them. Over the years, Cummins has continued to improve the efficiency of the diesel engine, providing technological innovations. Their engines have set a high standard for the industry, exceeding the requirements of the Clean Air Act of 1970.

Mercedes Benz began building diesel driven automobiles in the mid 1930's. These were dependable, enduring automobiles that lasted well into the second half of the century. Early American Ford automobiles were not diesel driven, but they were powered by the biomass fuel, ethanol. Henry Ford shared a similar vision with Rudolph Diesel. He believed plant-based fuel to be the basis of the transportation industry. In a partnership with Standard Oil, he helped further the bio-fuel industry in the mid-west, encouraging development of production plants and distribution stations. But, along with biodiesel, this vision was obliterated by the petroleum industry and ethanol disappeared from the scene. Europe remained the leader in the development and production of diesel and biomass fuel engines for automobiles.

The 1970's arrived and the American people, who were firmly dependent on foreign oil, yet, unaware of the depth of their dependence, were suddenly faced with a crisis. In 1973, OPEC (Organization of the Petroleum Exporting Countries), the Middle Eastern organization controlling the majority of the world's oil and India's main supplier, reduced the supply of oil and raised the price sending the United States into a crisis. This crisis was recreated in 1978. Long lines at the gas pumps occurred. People panicked as they realized their whole infrastructure depended on the consistent supply of oil - foreign oil- to their economy, conservation and alternatives became important.

The American public looked to diesel fuel which was more efficient and economical and they began buying diesel-powered automobiles. These automobiles accounted for 85% of Peugeot's sales, 70% of Mercedes Benz's sales, 58% of Isuzu's sales, 50% Volkswagen's sales, plus a good portion of Audi's, Volvo's and Dotson's sales during the 1970's. For the first time, an American manufacturer began producing an automobile with a diesel engine. General Motors made and sold diesel automobiles in the late 1970's, accounting for 60% of all diesel sales in the United States. This surge of diesel sales in American ended in the 1980's. The price of oil had been re-stabilized and the immediate need for conservation receded in the American consciousness. Along with this, the automobiles produced by General Motors were basically converted gasoline engines. The higher compression of the diesel combustion caused blocks to crack and crankshafts to wear out prematurely. GM ended production of its diesel automobiles in 1985.

As we entered the 21st Century, only Mercedes Benz and Volkswagen made diesel automobiles for export to the United States. Sales accounted for less than 6% for Mercedes Benz and less than 5% for Volkswagen. A few light trucks utilizing diesel engines were made by American manufacturers, but no automobiles. Diesel engine efficiency and durability kept them the engine of choice for trucks, heavy machinery, and marine engines. The marketing of the petroleum industry, the American desire for immediacy and ease have kept the use of the diesel engine from becoming part of the consciousness of the general population here in America.

Looking to the future, our relationship with the oil industries and dependency on foreign oil, hopefully, will drive us to explore alternatives with a more open mind.

2.2 Evolution of Biodiesel as an Alternative Fuel

Natural resources that our nation relies heavily upon such as oil, petroleum and natural gas are fossil fuels. This means that they will eventually cease to exist. This gives much economic and political power to the nations that have an abundance of these natural resources. The thought of this supply ending also causes a search for renewable resources that would never cease to exist. Petroleum or "black gold" provides the world with nearly half the energy used. 67% of the world's oil reserves are found in the Middle East. Saudi Arabia alone has one fourth of the world's oil. One tenth of the world's oil is found in Abu Dhabi, Iran, Iraq, and Kuwait. Compared with this extensive supply, the U.S. and Canada have only 3% of the world's reserves. Despite this, the U.S. and Canada consume more than four times the amount of petroleum than the Middle East.

It is often reported that Rudolph Diesel designed his engine to run on peanut oil, but this is not the case. Diesel stated in his published papers that Otto Company showed a small Diesel engine, which, at the request of the French government was run on arachide (earth-nut or pea-nut) oil. It worked so smoothly that only a few people were aware of it. The engine was constructed for using mineral oil, and was then worked on vegetable oil without any alterations being made. The French Government at the time thought of testing the applicability to power the production of the Arachide, or earth-nut, which grows in considerable quantities in their African colonies, and can easily be cultivated there. Diesel himself later conducted related tests and appeared supportive of the idea. During a speech delivered in 1912, Rudolph Diesel said, "the use of vegetable oils for engine fuels may seem insignificant today but such oils may become, in the course of time, as important as petroleum and the coal-tar products of the present time" **(Bijalwan et al [2])**.

Despite the widespread use of fossil petroleum-derived diesel fuels, interest in vegetable oils as fuels for internal combustion engines was reported in several countries during the 1920's and 1930's and later during World War II and 1970's oil crisis. Belgium, France, Italy, the United Kingdom, Portugal, Germany, Brazil, Argentina, Japan and China were reported to have tested and used vegetable oils as diesel fuels during this time. Some operational problems were reported due to the high viscosity of vegetable oils compared to petroleum diesel fuel, which results in poor atomization of the fuel in the fuel spray and often leads to deposits and coking of the injectors, combustion chamber and valves **(De Carvalho Macedo [3], Senthilkumar [4])**. Attempts to overcome these problems included heating of the vegetable oil, blending it with petroleum-derived diesel fuel or ethanol, pyrolysis and cracking of the oils.

On 31st August 1937, G. Chavanne of the University of Brussels (Belgium) was granted a patent for a "Procedure for the transformation of vegetable oils for their uses as fuels". This patent described the alcoholysis (often referred to as transesterification) of vegetable oils using ethanol in order to separate the fatty acids from the glycerol by replacing the glycerol with short linear alcohols. The transesterfication reaction is the basis for the production of modern biodiesel. **(Korbitz [5])**

More recently, in 1977, Brazilian scientist Expedito Parente invented and submitted for patent, the first industrial process for the production of biodiesel. This process is classified as biodiesel by international norms, conferring a standardized identity and quality. No other proposed bio fuel has been validated by the motor industry. Currently, Parente's company Tecbio is working with Boeing and NASA to certify bioquerosene (bio-kerosene), another product produced and patented by the Brazilian scientist.

Research into the use of transesterified sunflower oil, and refining it to diesel fuel standards, was initiated in South Africa in 1979. By 1983, the process for producing fuel-quality, engine-tested biodiesel was completed and published internationally. An Austrian company, Gaskoks, obtained the technology from the South African Agricultural Engineers and erected the first biodiesel pilot plant in November 1987, and the first industrial-scale plant in April 1989 (with a capacity of 30,000 tons of rapeseed per annum).

In 1991, the European Community proposed a 90% tax reduction for the use of bio fuels, including biodiesel. Today 21 countries worldwide produce biodiesel. Throughout the 1990's, plants were opened in many European countries, including the Czech Republic, Germany and Sweden. France launched local production of biodiesel fuel (referred to as *diester*) from rapeseed oil, which is mixed into regular diesel fuel at a level of 5%, and into the diesel fuel used by some captive fleets (e.g. public transportation) at a level of 30%. Renault, Peugeot and other manufacturers have certified truck engines for use with up to that level of partial biodiesel; experiments with 50% biodiesel are underway.

In 1997, Kyoto Protocol prompted resurgence in the use of biodiesel throughout the world. Under the Protocol, 37 countries commit themselves to a reduction of four greenhouse gases (GHG) (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) and two groups of gases (hydrofluorocarbons and perfluorocarbons) produced by them, and all member countries give general commitments. During the same period, nations in other parts of the world also saw local production of biodiesel starting up: by 1998, the Austrian Biofuels Institute had identified 21 countries with commercial biodiesel projects. 100% Biodiesel is now available at many normal service stations across Europe.

In September 2005 Minnesota became the first U.S. state to mandate that all diesel fuel sold in the state contain part biodiesel, requiring a content of at least 2% biodiesel. In 2008, ASTM published new Biodiesel Blend Specifications Standards.

Since biodiesels have different physical and chemical properties compared to petroleum based diesel fuels, the use of biodiesel in the engine will affect the performance and emissions of the engine. To study this effect, more research is required in order to ensure that pure biodiesel can be used in any engine without any major hardware modifications. A large number of experimental studies are reported to study the thermal performance of biodiesel blended fuel used in diesel engine operated at constant compression ratio. Studies on variable compression ratio diesel engine however, are relatively few.

The diesel fuel consumption in India is about five times higher than gasoline fuel (Table 2.1). The demand of high-speed diesel has been estimated to be 66.9Mt for the year 2011–2012, which would be 1.6 times higher than that of current demand. The cost of the diesel fuel increases due to the increase in crude oil price and processing costs such as desulphurization in order to meet stringent emission norms etc. So, it is necessary to take appropriate policy decisions in the country to fulfil future demand of diesel fuel in view of improving fuel quality and stringent emission norms. Therefore, biodiesel and ethanol are being considered to be supplementary fuels to the diesel in the country. In addition to that, these biofuels are being looked to provide employment generation to rural people through plantation of vegetable oils and can be beneficial to sugarcane farmers through the ethanol program.

Table 2.1 Demand of Gasoline and Diesel in India (Courtesy IOC)

Year	Gasoline demand in million tonnes	Diesel demand in million tonnes	Ratio of Diesel/Gasoline
2002-2003	7.62	42.15	5.53
2003-2004	8.20	44.51	5.42
2004-2005	8.81	46.97	5.33
2005-2006	9.42	49.56	5.26
2006-2007	10.07	52.33	5.20
2011-2012	12.85	66.90	5.21

Biodiesel can be derived from vegetable oils and fats. India has about 100 Mha degraded land which can be utilized for producing raw material for biodiesel. Biodiesel has higher flash point temperature, higher cetane number, and lower sulphur content and lower aromatics than that of petroleum diesel fuel **(Sharp [6])**. It could also be expected to reduce exhaust emissions due to fuel containing oxygen. The main problems of current Indian diesel fuel are low flash point (35 ^{0}C against world average of 52 ^{0}C) and high sulphur content which can be improved by blending it with biodiesel. In this regard, a typical data related to trends in improvements in cetane number, flash point and sulphur content by blending biodiesel are given in Table 2.2.

Table 2.2 Properties of Diesel, Biodiesel Blend (B20) and Biodiesel [6]

Properties	Diesel	B20	B100
Cetane number	43.3	46	47.5
Flash Point (^{0}C)	62	90	146
Sulphur wt (%)	0.0476	0.037	0.00

It is well established that significant reductions in emissions can be achieved by use of biodiesel **(Graboski [7], Peterson [8])**. 13–66% reduction in PM with 2–11% increase in NO_x was reported by **Graboski [7]**. CO_2 emission by use of biodiesel in diesel engines will be recycled by the crop plant resulting to no new addition into atmosphere **(Peterson [8])**. The non-regulated emissions like polycyclic aromatic hydrocarbon (PAH), nitrate polycyclic aromatic hydrocarbon (nPAH), sulphate emission etc. are also significantly lower **(National Biodiesel Board [9])**.

India has varied resources for production of ethanol. Government of India has initiated 5% ethanol-blended petrol with effect from 1st January 2003 and 10% ethanol blended petrol is also being envisaged **(Vijayaraghava [10])**. Ethanol–diesel emulsion can also give beneficial results in terms of emission reduction in diesel engines **(Ahmed [11], Ali [12])**. 41% reduction in particulate matter and 5% NOx emission with 15% ethanol - diesel blends are reported **(Ahmed [11])**. Net savings of 20% in CO_2 emissions was achieved in Brazil due to ethanol and bagasse substitution from fossil fuels **(De Carvalho Macedo [3])**. Biodiesel generally causes a decrease in emission of hydrocarbons (HC) and carbon monoxide **(Schumacher et al. [13])**. Therefore, blending of ethanol even in small quantity could give beneficial results.

2.3 Experimental Studies Using Biodiesel as Fuel

This section deals with the brief reviews of studies conducted on thermal performance, emission characteristics and combustion analysis of biodiesel fuelled diesel engines. Studies on thermal performance and emission characteristics are reviewed in Section 2.3.1 and studies on combustion analysis are reviewed in Section 2.3.2.

2.3.1 Thermal Performance and Emissions

Since the time of realisation that there is a need to find alternative fuels, a number of investigators have made attempts to replace diesel with a substitute such as vegetable oils and biodiesels. This section deals with an exhaustive review of the experimental studies conducted by noted investigators on performance and emission characteristics of diesels engines fuelled with variety of biodiesels and vegetable oils. From the review, it is found that generally biodiesels and vegetable oils are used in blended form with diesel to run on the engines. The biodiesels which can be found in this review are based on the seed oils of Rapeseed, Jatropha, Mahua, Karanja, Cottonseed, Tobacco, Ricebran, Tall, Polanga, Soybean, Castor, Sunflower, Sesame, Canola, Palm, Salmon, Rubberseed etc. The studies are generally conducted on the engines by varying load, speed, torque, compression ratio, brake mean effective pressure or brake power in suitable steps and in suitable range. The performances are generally judged based on the specific fuel consumption and brake thermal efficiency and exhaust gas temperature. The exhaust emissions, most investigators considered, are carbon monoxide, unburnt hydrocarbon, oxides of nitrogen and Smoke opacity.

Mc Donnel et al [14] investigated the use of semi-refined rapeseed oil on a diesel engine. They reported that engine performance was better at 25% blend. The use of rapeseed oil over a longer period of time was found to shorten the injector life due to carbon build up even though there was no wear on the engine components or lubricating oil contamination.

Kalam and Masjuki [15] experimented Palm biodiesel on an indirect injection, naturally aspirated, four cylinder, compression ignition engine. The Compression ratio (CR) and rated power of the engine was respectively 21:1 and 39kW at 5000rpm as rated speed. It was found that brake power increases with increase in the concentration of palm biodiesel (POD) in the blend of ordinary diesel (OD) and palm biodiesel. Along with POD, two other fuels were also tested. One of them was fuel A which contained 50ppm (corrosion inhibitor) additive, 7.5% POD and 92.5% OD and the other was fuel B which contained 50ppm (corrosion inhibitor) additive, 15% POD and 85% OD. Fuel B produced maximum brake power (12.4 kW) at 1600 rpm followed by fuel A (11.4 kW) and fuel OD (10.48 kW). The reason for higher brake power was stated as the effect of addition of corrosion inhibitor in POD blends that influences conversion of heat energy to work. It was stated that POD blends with corrosion inhibitor additive could be effective as alternative fuels for diesel engines because they reduce emissions levels such as those of NO_x, CO and HC. A Multi-element oil analyzer was used to measure wear debris and additives depletion. It was observed that wear metals debris such as Fe, Cu, Al, Pb reduced with increasing POD into the blends. The reason for this was stated as the effect of corrosion inhibitor in fuel which controlled corrosion as well as oxidation in lubricating oil. Fuel B produced the lowest level of wear concentration followed by fuel A and OD. It was concluded that using an anti corrosion additive with POD blends is always effective.

Senthil Kumar et al. [16] experimented with various methods of using vegetable oil (Jatropha oil) and methanol such as blending, transesterification and dual fuel operation. A single cylinder direct injection diesel engine was used for this work and was tested at constant speed of 1500 rpm at varying power outputs. The ratio of methanol to Jatropha oil was maintained as 3:7 on the volume basis. The brake thermal efficiency (BTE) increased from 27.4% with neat Jatropha oil to a maximum of 29% with the methyl ester and 28.7% in the dual fuel operation. The smoke emission were 4.4 Bosch Smoke Units (BSU) with neat Jatropha oil, 4.1 BSU with the blend, 4 BSU with methyl ester of Jatropha oil and 3.5 BSU in the dual fuel operation. The nitric oxide (NO) emissions were lower for Jatropha oil compared to diesel. It was further reduced with dual fuel operation and blending with methanol. This was attributed to reduction in charge temperature due to vaporisation of methanol. Dual fuel operation showed higher hydrocarbon and carbon monoxide emissions than the ester and the blend. This was attributed to the quenching of methanol air flame on the walls and also due to low temperature. The final conclusion drawn from the study was that Jatropha oil can be used as fuel in diesel engines directly and by blending it with methanol. Also use of methyl ester of Jatropha oil and dual fuel operation with methanol induction gives better performance and reduced smoke emissions than blend.

Raheman and Phadatare [17] conducted a study on performance and emissions of a diesel engine by using Karanja methyl ester as fuel. Karanja oil was esterifed using the esterification system developed in the laboratory of Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur. The system was capable of preparing the oil esters sufficient in quantity for running commonly used farm engines (3:73 kW) for at least 8 hrs. The engine used for conducting the study was a single cylinder, four-stroke, DI, water-cooled diesel engine having a rated output of 7.5 kW at

3000 rpm and a compression ratio of 16:1. The minimum and maximum CO produced were 0.004%, 0.016% for pure Karanja methyl ester resulting in a reduction of 94% and 73%, respectively, as compared to diesel. The minimum and maximum smoke densities produced for B20 to B100 were 1% and 3% with a maximum and minimum reduction of 80% and 20%, respectively, as compared to diesel. On an average, a 26% reduction in NO_x was obtained for biodiesel and its blends as compared to diesel. For B20–B100, the exhaust temperature measured varied between 260°C and 336°C as compared to 262°C and 335°C for diesel indicating no much variation in exhaust temperature. For an average speed of 2525 rpm (±2%), Brake specific fuel consumption (BSFC) for B20 and B40 was found 0.8–7.4% lower than diesel. In case of B60–B100, the BSFC was found 11–48% higher than that of diesel. This reverse trend was observed due to the lower calorific value with an increase in biodiesel percentage in the blends. The maximum BSFCs were found to be 26.79% and 24.62% for B20 and B40, respectively, which were higher than that of diesel (24.62%). The maximum BSFCs found for B60, B80 and B100 were 24.26%, 23.96 and 22.71%, respectively. This lower BTE obtained for B60–B100 could be due to a reduction in the calorific value and an increase in fuel consumption as compared to B20. The maximum BTEs found for B60, B80 and B100 were 24.26% 23.96 %and 22.71%, respectively.

Carraretto et al. [18] presented the results of an investigation carried out on the potentialities of biodiesel as an alternative fuel based on strategic considerations and field experiences in boilers and diesel engines. The operation of a biodiesel fuelled boiler was checked for some months. The engines were bench-tested and then installed on urban buses for normal operation. Distances, fuel consumption and emissions (CO_2, CO, HC and NO_x) were monitored. Also wear and tear on devices, oil and air filters dirtiness and lubricant degradation were checked. The efficiency of the ''biodiesel'' boiler is always higher than that of the ''diesel'' one and does not decrease significantly with time. The increased efficiency is connected with the lower temperature of the gases at the stack. The emissions of CO and CO_2 are very similar for the two boilers. The diesel engine used for experimentation was UNIC 8220.12, six cylinder, four stroke, direct injection diesel engine with a compression ratio of 17:1. The engine could produce a maximum power of 158 kW at 2600 rpm and was widely used on local urban buses. The tests were carried out using different blends of biodiesel and diesel oil i.e. 100%, 80%, 70%, 50%, 30%, 20% and 0% volume of biodiesel. The increase of biodiesel percentage in the blend led to a slight decrease of both power and torque over the entire speed range.

A significant increase of SFC over the entire speed range was registered with biodiesel (about +16% average), due to its lower heating value and greater density. However, by reducing the injection advance, it was possible to optimize combustion, improving performances especially at low and medium speed. By reducing the injection angle with respect to nominal injection advance operation, power and torque were found to be increased up to almost the levels of pure diesel oil while SFC was reduced. CO emissions were reduced but NO_x were increased with the use of biodiesel. The reduction in CO was attributed to complete combustion and increase in NO_x was attributed to higher cylinder temperatures.

Nwafor [19] studied the emission characteristics of a diesel engine fuelled with rapeseed oil. The high viscosity of the rapeseed oil was reduced by increasing the inlet temperature of vegetable oil fuel. The results of unheated rapeseed oil, heated rapeseed oil and neat diesel were compared on the same plot. It was found that with the increase in load, the CO emissions increased for unheated oil and diesel while it reduced at low loads for heated and then increased for higher loads. The CO_2 emission plots did not show any major difference between the fuels at low loading conditions but at high loading levels heated fuel showed increase in CO_2 emissions compared to other fuels. The investigator stated that less cone angle of the fuel spray, less viscosity and efficient combustion were the reasons for high CO_2 emissions. The hydrocarbon emissions were highest for diesel fuel by a factor of 2.5 compared to vegetable oil fuels. At low loading conditions, the HC levels were similar for both heated and unheated fuels while at high loading conditions the heated fuel showed higher HC levels compared to unheated fuel. The Exhaust gas temperature (EGT) was highest for heated fuel followed by unheated fuel and diesel. The overall test results showed that the heating of vegetable oil was beneficial at all loading conditions.

Pradeep and Sharma [20] conducted a test on a single cylinder diesel engine running on rubber seed oil and its blends with diesel. BTE was found lower for bio-diesel blends compared to diesel. Higher combustion duration and lower heat release rate were recorded for bio-diesel.

Ramadhas et al [21] conducted a performance and emissions study on a Canon make four stroke, direct injection, naturally aspirated single cylinder diesel engine using methyl esters of rubber seed oil. The rated power of the engine was 5.5kW and the rated speed was 1500 rpm. The means of loading was an electric generator. The maximum

BTE obtained was about 28% for B10, which was around 25% higher than that of diesel. In case of B50 to B100, the BSFC was found to be higher than that of diesel. At maximum load condition, the BSFC of 100% biodiesel was more than 12% than that for diesel. It was noted that, the engine emits more CO using diesel as compared to that of biodiesel blends under all loading conditions. With increasing biodiesel percentage, CO emission level decreased. B20 blends gave smoke density of 28% as compared to 45% in the case of diesel. It was found that biodiesel fuelled engines emit more NOx as compared to that of diesel fuelled engines.

Usta [22] carried out an experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester (TSOME). A four cylinder, four stroke turbocharged indirect injection diesel engine was used for the experimental study. Maximum efficiency was generated with the D82.5/TSOME17.5 fuel. The TSOME blends resulted in slightly higher torque and power than the diesel fuel at full load due to its slightly higher density and viscosity. The investigators observed that the turbocharged diesel engine used in the experiments supplied more air at the higher speeds resulting in an increase of turbulence intensity in the combustion chamber. This enabled more complete combustion. Therefore, the beneficial effect of TSOME as an oxygenated fuel was partially lost at high speeds. Since TSOME contains about 11.4% oxygen by weight and this oxygen helps to oxidize the combustion products in the cylinder, especially in rich zones, the addition of TSOME decreased CO emission. Also, TSOME has fairly low sulphur, and therefore, the diesel/TSOME fuel blends resulted in significant SO_2 reduction. Although there has not been a significant difference in NO_x emissions at partial loads, NO_x is slightly increased due to the higher combustion temperature and the presence of fuel oxygen with the blend at full load. At partial loads, the TSOME addition resulted in slight decreases in power, torque and thermal efficiency due to the dominant premixed lean combustion with excess oxygen. This indicated that the addition of TSOME is most effective in rich combustion.

Puhan et al. [23] studied the performance of Mahua oil methyl ester (MOME) in comparison with diesel fuel. The compression ignition engine used for the study was Kirloskar, single cylinder, four stroke, constant speed, vertical, water cooled, direct injection type.. The engine was coupled to a swinging field separating, exciting type DC generator and loaded by electrical resistance bank. It was found that BSFC for MOME is higher than diesel. This according to the investigators was due to the fact that esters have lower heating value compared to diesel so more ester-based fuel is needed to maintain constant power output. They also found that the NO_x emissions reduced in case of biodiesels. The reduction in NO_x was around 4% in case of MOME. It was observed that around 11% reduction in smoke number produced in MOME compared with diesel. The specific fuel consumption is higher (20%) than that of diesel and thermal efficiency is lower (13%) than that of diesel. Exhaust pollutant emission are reduced compared to diesel. Carbon monoxide, hydrocarbon, smoke number, oxides of nitrogen were reduced by 30%, 35%, 11%, 4%, respectively, compared to diesel.

Duran et al [24] studied the effect of specific fatty acid methyl esters present in biofuels on particulate matter emissions. The oxygen content of the fuel is taken into account by considering the transesterified oil composition (palmitic, oleic and linoleic acids methyl esters content, which were selected for summing up to 90% of all esters present in oils). The experiments were performed on a Nissan YD2.2 direct injection turbocharged engine. 30% of reduction in particulate emissions is attained when only 8 Wt % of Palmitic acid Methyl Ester (PME) is added to the reference fuel. The effect of Oleic acid Methyl Ester was found to be important only when PME is present in small proportions. The oleic acid methyl ester produced a slighter but more prolonged decrease in particulate formation. Indeed, Cetane Numbers (CNs) for methyl esters of palmitic, oleic and linoleic acids are 85.9, 59.3 and 38.2, respectively. This would imply a better combustion if an increase in PME concentration was made with the consequent decrease in particulate matter emissions. Simulation from NNs equations proved that the amount of palmitic acid methyl ester in fuels is the main factor affecting the amount of insoluble material emitted due to its higher oxygen content and cetane number.

Labeckas and Slavinskas [25] conducted a comparative analysis of the effect of two different biofuels as diesel fuel (80vol%) and rapeseed methyl ester (20vol%) (RME20) as well as diesel fuel (75vol%) and rapeseed oil (25vol%) (RO25) blends on the economical and ecological parameters of a 59KW high-speed direct-injection diesel engine when operating at a wide range of loads and speeds. At the minimum speed of 1400 rpm and maximum load of BMEP 0.77 MPa the BSFC was found to be lower by 1.6% for blend RME20 and higher by 2.3% for RO25 related to diesel fuel where the value was 238 g/kWh. The maximum NO_x emissions generated from a heavy loaded engine run on blend RME20 at speeds 1400, 1800 and 2200 rpm were higher by 1.4%, 23.7% and 44.7% whereas when fuelling it with blend RO25 the top NOx emission levels were found as 37.4%, 26.7% and 11.7% lower related to diesel fuel.

Usta et al. [26] investigated the effects of the methyl ester produced from a hazelnut soap stock/waste sunflower oil mixture using methanol, sulphuric acid and sodium hydroxide in a two stage process on the performance and emissions of a Ford XLD 418T four cycle, four cylinder, turbocharged indirect injection (IDI) Diesel engine at both full and partial loads. From the results, it was observed that even if addition of the biodiesel to the diesel fuel decreases its heating value, higher power was obtained in the experiments. This was due to higher oxygen content of biodiesels according to the investigators. The CO emissions of the blend were higher than those of diesel fuel between 1500 and 2200 rpm speeds at full and 75% loads, while they were lower than those of diesel fuel at higher speeds. The SO_2 emissions of the blend were lower than those of the diesel fuel. The NOx emissions of the blend were slightly higher than those of the diesel fuel at both full and partial loads. The noise measurements were taken 1 m away from the engine in the engine room by using a sound level meter. The biodiesel addition slightly decreased the noise. The reduction was less than 1 dB in the range of engine speeds tested.

Reddy and Ramesh [27] studied the effect of injection timing, injector opening pressure, injection rate and air swirl level on the performance of Jatropha oil fuelled diesel engine. The engine used to conduct the experiments was a single cylinder, constant speed, direct ignition diesel engine. For varying the injection timing the position of the fuel injection pump was changed with respect to the cam. The injection was varied by changing the diameter of the plunger of the fuel injection pump. A masked inlet with proper orientation was used to create a swirl of air. The observations made in this study were as follows. The BTE increased, HC and smoke emissions reduced with advanced injection timing and increased Injection Pressure (IP) whereas enhancing the swirl had only a small effect on emissions.

Yoshimoto [28] conducted an experiment on single cylinder diesel engine to investigate the spray characteristics, engine performance, emissions and combustion characteristics of water emulsions of the blended fuel with equal proportions of rapeseed oil and diesel.

The researcher found that the performance was improved with slightly increased emissions of CO and NO_x with knock free combustion.

Reyes and Sepulveda [29] conducted a study on particulate matter emissions and power of a diesel engine using salmon oil. The fuel tests were performed on a 5959 cm^3, six cylinder, four stroke, water cooled diesel engine Mercedes Benz Model OM-366. The fuels used were diesel-crude biodiesel (B) and diesel-refined biodiesel (M). The maximum engine power was 100 kW at 2200 rpm. It was observed that the maximum power slightly decreased when percentage of crude biodiesel was increased in the fuel blend. Particulate material emission tests were carried out by measuring opacity of the exhaust gases. 100% of refined biodiesel permits reduction of up to 50% of particulate emission and non critical 3.5% of loss in power with a very good specific fuel consumption. In comparison to crude biodiesel from salmon oil, refined biodiesel has a unique economic disadvantage of the cost involved in distillation of the crude biodiesel, condition that will determine its applicability depending on the eventual cost of diesel fuel. From this study, it was found out that the blends M-100, M-40 and B-100 emerge, respectively, as possible advantageous alternatives according to its particulate emission performance. The blends B-40, B-60 and B-80 were critically near the limit of emission requirements normative for the engine tested at maximum power. However all the blends are in accordance with the official requirements under partial load and free acceleration conditions of the tested engine.

Li and Lin [30] used a biodiesel produced using peroxidation process. The fuel properties, engine performance and emission characteristics of ASTM No. 2D diesel, a commercial biodiesel, biodiesel with and without the peroxidation were analyzed and compared. The peroxidised biodiesel gave higher thermal efficiency than diesel. This was due to higher oxygen content and higher cetane number of biodiesel. The emission indices of CO_2 and CO as well as the exhaust gas temperature were lower for biodiesel than compared to diesel. They concluded that the peroxidation technique is capable of effectively improving fuel properties and reducing the emission pollution of biodiesel.

Crookes et al. [31] presented the results of his experiments conducted on spark-ignition engines and compression ignition engines using variety of biofuels. The biofuels tested were biogas containing carbon dioxide, simulated biogas, commercially available seed oil and rape-seed methyl ester (RME). The oxides nitrogen were less for biogas fuelled engine while unburned hydrocarbons were increased compared to natural gas fuelled engine. With the increase in CO_2 fraction in biogas the brake power remained unchanged and BSFC increased. When CR was increased, oxides of nitrogen are reduced. Diesel fuel and edible-grade seed oil (equal volumes of rape seed and soya oils)-base fuels and blends of these containing 25% and 75% seed oil were tested in compression ignition engine. With the increase in vegetable oil fraction in the blend NO_x increased and smoke number reduced. The baseline data obtained for diesel fuel was also compared with the results obtained for RME biodiesel. It was found that RME produced more NO_x and lower smoke reading compared to diesel.

Rakopoulus et al. [32] conducted an extensive study to evaluate and compare the use of biodiesels of various origins as alternatives to conventional diesel fuel at blend ratios of 10/90 (10% biodiesel and 90% diesel) and 20/80 in a Direct injection (DI) diesel engine. The fuels tested were cottonseed oil, soybean oil, sunflower oil and their corresponding methyl esters as well as methyl esters of rapeseed oil, palm oil, corn oil and olive kernel oil. A series of tests were conducted using each of the fuel blends on the engine working at a speed of 2000rpm and at a medium and high load. In each test, exhaust smokiness, exhaust gas emissions such as NO_x, CO and total unburned HC were measured. Brake specific fuel consumption (BSFC) and brake thermal efficiency were also computed. The smoke intensity was significantly reduced with the use of biodiesel blends with respect to that of neat diesel and this reduction was found to be higher with higher percentage of bio-diesels in the blend. On the contrary, the smoke intensity increased with the use of vegetable oils blends and it increased with increase in the percentage of vegetable oil in the blends. The NO_x emissions were slightly reduced with the use of biodiesels or vegetable oils with respect to that of neat diesel fuel and this reduction was found to be higher with higher percentage of biodiesel or vegetable oil in the blend. The CO emissions reduced with the use of biodiesels and this reduction was higher with higher percentage of biodiesel in the blend. On the contrary, the CO emissions increased with the use of vegetable oil and this increase was proportional to the increase in percentage of vegetable oil in the blend. The unburned HC levels observed were very small and they did not show any specific trend for biodiesels or vegetable oils. The performance of the engine operated with biodiesels and vegetable oils was similar to that when operated with neat diesel fuel giving nearly same BTE. However the BSFC was found to be higher in case of high load. For medium load conditions, BSFC was found to be minimum for 10/90 blend. It was concluded that irrespective of the raw feedstock material all tested, biodiesels and vegetable oils can be used safely and advantageously in the diesel engines at least in small blending ratios with normal diesel fuel.

Dwivedi et al. [33] set out a study to characterize particulate emissions from diesel engines fuelled by (i) mineral diesel and (ii) B20 (a blend of 20% biodiesel with diesel); in terms of metals and benzene soluble organic fraction (BSOF), which is an indicator of toxicity and carcinogenicity. A medium duty, transport diesel engine (Mahindra MDI 3000) was operated at idling, 25%, 50%, 75% and 100% rated load at maximum torque with a speed of (1800 rpm). Samples of particulate were collected using a partial flow dilution tunnel for both fuels. Collected particulate samples were analyzed for their metal contents. In addition, metal contents in mineral diesel, biodiesel and lubricating oil were also measured to examine and correlate their (metals present in fuel) impact on particulate characteristics. Results indicated comparatively lower emission of particulate from B20-fuelled engine than diesel engine exhaust. Metals like Cd, Pb, Na, and Ni in particulate of B20 exhaust were lower than those in the exhaust of mineral diesel. However, emissions of Fe, Cr, Ni Zn, and Mg were higher in B20 exhaust. This reduction in particulate and metals in B20 exhaust was attributed to near absence of aromatic compounds, sulphur and relatively low levels of metals in biodiesel. However, benzene soluble organic fraction (BSOF) was found higher in B20 exhaust particulate compared to diesel exhaust particulate.

Pereira and Oliveira [34] presented their experimental investigation concerning the electric energy generation using diesel and soybean bio-diesel as fuel. For all tests conducted, the electric energy generation was assured without problems and it was observed that the emission of CO, HC and SO_X decrease and temperature of exhaust gases and the emissions of NO and NO_X were comparable to or less than that of diesel. The values of exhaust emissions are given in Table 2.3.

Table 2.3 Comparison of Exhaust Emissions Due to Diesel oil and Biodiesel Blends [34]

Parameters	Diesel	B20	B50	B75	B100
O_2 (%)	19.1	19.1	19.2	19.2	19.3
CO_2 (%)	1.38	1.45	1.39	1.77	1.68
CO (ppm)	174	144	102	160	156
SO_2 (ppm)	5.7	3	2	1.3	2.7
NO (ppm)	446	410	438	445	407

C_xH_y (ppm)	103	102	102	84	70
Exhaust gas temperature (^0C)	141.4	129.5	129	132.7	135
Test room temperature (^0C)	32.4	34.4	39.1	28.3	27.8

Altiparmak et al. [35] experimented with tall oil methyl ester–diesel fuel blends as alternative fuels for diesel engines. Low sulphur and aromatic contents are advantages of tall oil fatty acid methyl ester–diesel fuel blends. It was reported that at high engine speeds, torque and engine power output increased by 6.1% and 5.9%, respectively, with blended fuels in comparison with diesel. At low engine speeds, specific fuel consumption increased with blended fuels depending on the amount of tall oil methyl ester. But, relative to diesel fuel, specific fuel consumption for blended fuels did not increase significantly at higher engine speeds. It was concluded that blended fuels can be used without any modifications in diesel engines. With the use of Tall oil methyl ester–diesel fuel blends decreasing CO emissions were decreased up to 38.9%. Higher NO_X concentrations in exhaust gas were obtained with all blended fuels. NO_x concentration was increased up to 30% depending on the amount of TOME. Compared with the diesel fuel, lower smoke opacity was obtained with blended fuels. Amongst the blended fuels, lower opacity was obtained with 30% D2–70% TOME, especially at middle and higher engine speeds.

Sahoo et al. [36] tested high acid value Polanga (Calophyllum inophyllum L.) oil based mono esters produced by triple stage transesterification process and blended with high speed diesel on a small-size water-cooled direct injection diesel engine. The density and viscosity of the Polanga oil methyl ester formed after triple stage transesterification were found to be close to those of petroleum diesel oil. Smoke emissions also reduced by 35% for B60 as compared to neat petro-diesel. Decrease in the exhaust temperature of a biodiesel-fuelled engine led to approximately 4% decrease in NOx emissions for B100 biodiesel at full load. The performance of biodiesel-fuelled engine was marginally better than the diesel-fuelled engine in terms of thermal efficiency, brake specific energy consumption, smoke opacity, and exhaust emissions including NO_x emission for entire range of operations. It was concluded that excess oxygen content of biodiesel played a key role in engine performance. Neat biodiesel was proved to be a potential fuel for complete replacement of petroleum diesel oil.

Karthikeyan and Mahalakshmi [37], tested turpentine (primary fuel) and high-speed diesel (pilot fuel) with sulphur contents 0.04 ppm on a Kirloskar TAF 1, single cylinder, constant speed (1500 rpm), direct injection engine with a bore of 87.5mm and a stroke of 110mm. This engine was modified to operate on a dual fuel (DF) mode. Usually, knock was suppressed in DF operation by adding more pilot-fuel quantity. In the present study, a minimum pilot-fuel quantity was maintained constant throughout the test and a required quantity of diluents (water) was added into the combustion at the time of knocking. The advantages of this method of knock suppression observed were restoration of performance at full load, maintenance of the same pilot quantity through the load range and reduction in the fuel consumption at full load. From the results, it was found that all performance and emission parameters of turpentine, except volumetric efficiency, were better than those of diesel fuel. The BTE of dual fuel engine at 75% load was 1–2% higher than that of diesel baseline. A maximum of 6% drop in volumetric efficiency was reported in DF engine at full load. In DF mode, an increase in fuel consumption was recorded beyond 75% load due to the occurrence of knock. However, proper quantity of diluents admission reduced the SFC and brought it closer to DBL. In this study, it was stated that the diluents admission at the time of knock prepares comparatively lean mixture inside the cylinder by diluting the air fuel mixture with the help of diluents resulting in a sluggish combustion and knock-free operation. The emissions like CO, UBHC were higher for DF operation than those of the diesel baseline (DBL) and around 40–45% reduction of smoke was observed at 100% of full load. The major pollutant of diesel engine, NO_x, was found to be equal to that of DBL. From the above experiment, it was proved that approximately 80% replacement of diesel with turpentine is quite possible.

Raheman and Ghadge [38] presented the performance and emissions of biodiesel obtained from Mahua oil (B100) and its blend with high speed diesel (HSD) in a Ricardo E6 engine. The BSFC, in general, was found to increase with the increasing proportion of Mahua biodiesel in the fuel blends with HSD, whereas it decreased sharply with increase in load for all fuels. The mean BSFC for the blends was higher than that of pure HSD by 4.3%, 18.6%, 19.6%, 31.7% and 41.4%, respectively, for every 20% additional blending of biodiesel in diesel. At full load conditions, the mean brake thermal efficiency of B100 was about 10.1% lower than that of HSD while at lower loads this variation was as high as 17.1%, which showed significantly lower efficiencies of B100 especially at lower loads. The mean temperature was found to increase linearly from 171 ^{0}C at no load to 285 ^{0}C at full load conditions with an average increase of 15% with every 25% increase in load. The reason for this increase in exhaust gas temperature with load was stated that as load increased more amount of fuel was required in the engine to generate that extra power needed to take up the additional loading. The mean EGTs of B20, B40, B60, B80 and B100 were 6%, 10%, 12%, 14% and 16% higher than the mean EGT of HSD, respectively. This, according to the investigators, could be due to the increased heat losses of the higher blends. It was seen that biodiesel and its blends with diesel produced less smoke than pure diesel. The minimum and maximum smoke densities produced for B20 to B100 were 7% and 34% with a maximum and minimum reduction of 46% and 5%, respectively, as compared to HSD. The minimum and maximum CO produced were 0.02–0.2% resulting in a reduction of 81% and 12%, respectively, as compared to diesel. These lower CO emissions of biodiesel blends were according to the author due to their more complete oxidation as compared to diesel. The amount of NO_x produced for B20 to B100 varied between 17 to 50 ppm as compared to 17 to 44 ppm for diesel. From the findings of this study, it was concluded that B100 could be safely blended with HSD up to 20% without significantly affecting the engine performance (BSFC, BTE, EGT) and emissions (Smoke, CO and NO_x) and thus could be a suitable alternative fuel for diesel.

Najafi et al. [39] conducted a comprehensive combustion analysis to evaluate the performance of a commercial DI, water cooled, two cylinders, in-line, naturally aspirated, RD270 Ruggerini diesel engine using waste vegetable cooking oil as an alternative fuel. In order to compare the brake power and the torque values of the engine, it was tested under same operating conditions with diesel fuel and waste cooking oil biodiesel fuel blends. The results were found to be very comparable. The properties of biodiesel produced from waste vegetable oil were measured based on ASTM standards. The total sulphur content of the produced biodiesel fuel was 18 ppm which is 28 times lesser than the existing diesel fuel's sulphur content used in the diesel vehicles (500 ppm). The maximum power produced was 18.2 kW at 3200 rpm using diesel fuel. The maximum torque produced was 64.2 Nm at 2400 rpm also using diesel fuel. By adding 20% of waste vegetable oil methyl ester, it was noticed that the maximum power and torque increased by 2.7 and 2.9% respectively, also the concentration of the CO and HC emissions have significantly decreased when biodiesel was used. It was stated that oxygen content in biodiesels is responsible for reduction in emissions.

Raheman and Ghadge [40] conducted performance tests on diesel engine with CR varied in the range from 18 to 20 and injection timings of 35° to 40° before top dead centre (TDC). The biodiesel used for this study was obtained from Mahua oil. The BSFC and EGT increased while BTE decreased slightly with increase in biodiesel proportion in the blend at lower CR and injection timings considered, where as these factors would show a reverse trend at higher CRs and advanced injection timings. It can be noticed that this value for B20 was 4.7% less than that of high speed diesel (HSD). The mean BTE of B20 was 0.9% higher than that of pure HSD. This could be attributed to the presence of increased amount of oxygen in B20, which might have resulted in its improved combustion as compared to pure diesel. Based on the results of this study, the performance of bio-diesel would be similar to diesel at higher CRs and advanced injection timings since bio-diesel is slightly more viscous. The effects of CR, the blend, injection timing and the load were discussed with respect to each performance parameter separately considered.

Roskilly and Nanda [41] investigated experimentally the application of bio-diesel from recycled cooking oil on small Marine craft diesel engines in UK as per the standard test procedure. An analysis of the performance and exhaust emission indicate that performance was comparable to that of diesel with an increase in rate of fuel consumption with a reduction in NO_x and CO emissions acting as contributors to greener environment. The biodiesel consumptions increased by 14.5–20.9%, over the load range compared to that when fuelled with fossil diesel. They also state that reduction in NO_X were due to smaller heating value and higher cetane number which provides shorter delay ensuring smooth combustion. The CO_2 emissions were 0.3% to 3.1% more when fuelled with biodiesel compared to that fuelled with fossil diesel over the load range. However, the CO_2 emissions from the biodiesel fuelled engines can be treated as ''zero net carbon emissions" and this advantage is the most important character of biodiesel compared to that of fossil diesel. This is because of oxygenated nature of biodiesel. The exhaust gas temperatures when fuelled with biodiesel were a little higher than that when fuelled with fossil diesel, ranging from 1.8% to 11.5%. The differences are not very significant. A slight modification in fuel injection system improves atomization with bio-diesel.

Ashok and Saravanan [42] conducted experiments by preparing blends of diesel ethanol emulsified fuel in proportion of 10, 20, 30 and 40 ethanol/diesel by volume and it was used to run a diesel engine at 1500rpm. The BTE is higher at the ratio of 70D: 30E

(70% diesel and 30% ethanol emulsified fuel) when compared with the sole fuel which is pure diesel. There is an increase of 3.45% efficiency of the emulsified fuel when compared with the sole fuel. BSFC is better for the ratio of 90D: 10E, when compared with sole fuel. There is a decrease in consumption of fuel of 0.11 kg/kW-hr for 90D: 10E. The effect of emulsified fuels on the performance and emission characteristics on the engine indicate that on the whole, use of emulsified fuel can significantly increase the BTE and BSFC .It also lowers the smoke density and exhaust gas temperature compared to neat diesel operation. There is rise of NO_X and particulate matter obtained, however this rise can be minimized by the usage of 80D: 20E emulsified fuel by adding the required additives. 80D: 20E was found to give good performance and low emission of the engine as compared to other D/E ratio fuel and neat diesel fuel. There was not much change in the variation of exhaust gas temperature for all ratios of emulsified fuel compared to that of neat diesel fuel which is important from exhaust emissions point of view.

Hasimoglu et al. [43] stated that though esterified fuels gives lower exhaust gas emissions and are biodegradable and renewable as compared to petroleum based diesel oil, viscosity and volatility problems still exist with these fuels. With the concept of a low heat rejection (LHR) engine (the engine that thermal barrier coating is applied is called low heat rejection (LHR) engine & the thermal barrier coated engine parts are piston, cylinder head, cylinder liners and exhaust valves)., the energy of bio-diesel can be released more efficiently thereby improving engine performance. In this experimental study, they used a turbo charged direct injection (DI) diesel engine ,converted to a LHR engine with thermal barrier coating running on sunflower oil bio-diesel as fuel. The results of this study indicated that the SFC and BTE were improved and the EGT was increased. Thermal barrier coatings were used to improve reliability and durability of hot section metal components and enhance engine performance and efficiency in internal combustion engines. Thermal barrier coatings are usually composed of a bond coat (NiCrAl) as an oxidation resistant layer and stabilized zirconia as a top coat that provides thermal insulation toward metallic substrate. Some important advantages of LHR engines are improved fuel economy, reduced engine noise, higher energy in exhaust gases (higher temperature of exhaust gases) and multi-fuel capability of operating low cetane fuels. With the application of the thermal barrier coating, the heating value of the mixture increased further for both fuels. The deterioration of the engine power and torque for biodiesel fuel was caused by the higher viscosity of the biodiesel. By the application of the thermal barrier coating, the engine power and torque were increased mainly due to the increased exhaust gas temperatures before the turbine inlet in LHR engine.

Banapurmath et al [44] conducted an experimental study on performance and emission characteristics of a DI compression ignition engine using methyl esters of Honge (Pongamia pinnata), Jatropha curcas (Ratanjyot) and Sesame (Sesamum indicum) oils. They suggested that the above bio-diesels could be used in its pure form or blended with diesel incorporating no major engine modifications since they have properties close to mineral diesel. Engine performed better with sesame oil bio-diesel as compared to the other two in terms of thermal efficiency, emission and combustion study. The maximum brake thermal efficiency was recorded with SOME and was 30.4% at 80% power output compared to 31.25% for diesel. All the esters resulted in slightly higher smoke emissions than diesel and were attributed to the incomplete combustion because of their lower volatility and higher viscosity. They found that HC and CO emissions were slightly more with karanja and jatropha as compared to sesame oil methyl ester. This was attributed to incomplete combustion because of higher viscosity, lower volatility and increased combustion duration with a comparable rate of heat release.

Velimir and Petrovic [45] states that air pollution in diesel engines is caused mainly by particulate matters and NO_X emissions. They have an adverse effect on environment and health. This study presents information on defining the best procedure and methodology for measurement of diesel engine particulate emissions. Euro 4 vehicle has 7.10^{13} particles/km and particulate matter of 18 mg/km under standard test conditions.

Utlu and Kocak [46] reported that waste frying oil methyl ester (WFOME) can be used as an alternative diesel engine fuel to operate a turbocharged direct injection diesel engine without modifications to engine or injection system. The lower heating value of WFOME is lower than that of diesel fuel. Since WFOME has a lower heating value, higher density and viscosity, WFOME's specific fuel consumption is increased by 14.34%. For both the fuels tested, minimum brake specific fuel consumption was obtained at 1750 rpm as 229.59 g/kWh for diesel fuel, and 258.66 g/kWh for WFOME? The emission values were decreased by 17.14% for CO, 1.45% for NOx. Smoke intensity is increased by about 22.46% for the utilization of WFOME compared to diesel fuel. Exhaust temperatures of WFOME were decreased on an average by 6.5% than diesel fuel. WFOME's power value was lower than diesel fuel. The decrease in average power was 4.5% with the use of WFOME. The investigators stressed that long period tests must be done for determination of WFOME's effect on fuel store, fuel systems' elements, engine oil & wear, injectors and burning combustion, pistons, manifolds and valves. This lower engine power obtained for WFOME could be due to fuel flow problems, as higher density, higher viscosity, and decreasing combustion efficiency as bad fuel injection may lead to reduced atomization and lower thermal efficiency than diesel fuel.

Ballesteros et al. [47] investigated important emissions such as total hydrocarbons (HC), particulate matter (PM), volatile organic fraction (VOF) and mean particle diameter (Dm) of PM for typical low sulphur diesel fuel available in Spanish petrol stations and for biodiesel fuel which was obtained from sunflower oil. Total HC emissions were determined in a regulated emissions bench from environment equipped with a flame ionization detector (FID) which, in addition to the total HC, also measures the amount of methane. The particulate matter was collected in a partial dilution mini-tunnel conditioned for the determination of PM emissions in diesel engines & the particle size distributions were determined in a scanning mobility particle sizer.

Gumus [48] used hazelnut kernel oil of Turkish origin to evaluate the performance of a DI diesel engine. Addition of Hazelnut Oil Methyl Ester (HOME) content in the blend, the BTE initially increased until it reached a maximum value at B20 blend and then decreased with increase of the HOME content in blend. Minimum BTE is obtained when neat HOME is used. Although addition of the HOME to the diesel fuel decreased its heating value, higher BTE was obtained for B5 and B20. The reason for this was that the biodiesel included approximately 10% (in weight) higher oxygen that could be used in combustion, especially in the fuel rich zone. This could be a possible reason for more complete combustion, thereby increasing the BTE. However, with more increase of HOME content in blend lower BTE was obtained for B50 and B100 due to the lower heating value and the higher viscosity, which resulted in slightly poorer atomization and poorer combustion. With increasing of HOME content in blend, negative effect of the lower heating value and the higher viscosity of HOME were more effective than positive effect of oxygen concentration included in HOME. The BSFC initially decreased slightly with the addition of HOME content in the blend until it reached 20% value but it increased with more enhancement of the HOME content owing to the lower calorific value and the higher viscosity of HOME. The EGT of B5 and B20 were found to be higher than diesel fuel in the high load owing to the higher viscosity which resulted in poorer atomization, poorer evaporation, and extended combustion which goes on at exhaust stroke. When HOME concentration is increased (B50, B100), the viscosity of blends increased even more and as a result of this, the EGT of blends were lower than EGT of diesel fuel due to more deterioration of combustion and oxidizing of more fuel. It was also found that with higher percentage of HOME blends low amount of CO_2 emissions took place as a consequence of higher viscosity of HOME. According to the researcher, due to the presence of oxygen in biodiesel the formation of smoke is restricted.

Kegl and Pehan [49] discussed the influence of biodiesel produced from rapeseed oil on the injection, spray, and engine characteristics with an aim to reduce harmful emissions. It was found that for biodiesel spray angle was narrower and the penetration length was larger. This was due to low fuel vaporization, worse atomization, and higher injection pressure of B100. Worse atomization was a consequence of high surface tension and viscosity of B100. This led to higher spray tip penetration. By using the engine without any modifications, biodiesel had a positive effect on CO and smoke emissions and on exhaust gas temperature at rated and peak torque conditions. The HC emission was increased at peak torque condition only. The thermal efficiency was practically unaffected, meanwhile the specific fuel consumption increases. Regarding the smoke and NO_x emissions, it can be concluded that B100 reduces smoke to a great extent, but increases the NO_x emission by about 5% at both tested regimes. The use of B100 increased the pump plunger surface roughness. However, this should not worsen the sliding conditions at the pump plunger walls. After biodiesel usage, the average value of root mean square roughness decreased which could be an indicator for even better lubrication conditions. In order to reduce all harmful emissions (of the considered engine), the injection pump timing has to be retarded from 23 to 19°CA BTDC. It has to be pointed out that by this modification the specific fuel consumption and other engine performances remained within acceptable limits.

Altun et al. [50] used a blend of 50% sesame oil and 50% diesel fuel as an alternative fuel in a direct injection diesel engine. Engine performance and exhaust emissions were investigated and compared with the ordinary diesel fuel in a diesel engine. The experiments were performed on a Lombardini 6 LD 400, one cylinder, four-stroke, air-cooled, direct injection diesel engine. It was found that the power produced by the blend of the sesame oil and diesel fuel was close to that of ordinary diesel fuel. The specific fuel consumption was higher for blended fuel than that of the ordinary diesel fuel. It was seen that the blended fuel emitted low CO values and slightly low NO_x values when compared with an ordinary diesel fuel. It was concluded that sesame oil and diesel fuel can be used as an alternative fuel successfully in a diesel engine without any modification and also it is an environmental friendly fuel in terms of emission parameters.

Correa and Arbilla [51] evaluated seven carbonyl emissions (formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, butyraldehyde, and benzaldehyde) by a heavy-duty diesel engine fuelled with pure diesel (D) and biodiesel blends (v/v) of 2% (B2), 5% (B5), 10% (B10), and 20% (B20). The tests were conducted using a six cylinder heavy-duty engine, typical of the Brazilian fleet of urban buses, in a steady-state condition under 1000, 1500, and 2000 rpm. The exhaust gases were diluted nearly 20 times and the carbonyls were sampled with SiO_2–C_{18} cartridges, impregnated with acid solution of 2,4-dinitrophenylhydrazine. The chemical analyses were performed by high performance liquid chromatography using UV detection. From the experimental results obtained it was found that formaldehyde was the most abundant carbonyl in the exhaust, followed by butyraldehyde, acetone + acrolein, acetaldehyde, propionaldehyde and benzaldehyde. In all biodiesel blends, it was found that total carbonyls emissions were higher in 1500 rpm than 1000 and 2000 rpm. Using average values for the three modes of operation (1000, 1500, and 2000 rpm) benzaldehyde showed a reduction on the emission (3.4% for B2, 5.3% for B5, 5.7% for B10, and 6.9% for B20) and all other carbonyls showed a significant increase: 2.6, 7.3, 17.6, and 35.5% for formaldehyde; 1.4, 2.5, 5.4, and 15.8% for acetaldehyde; 2.1, 5.4, 11.1, and 22.0% for acrolein+acetone; 0.8, 2.7, 4.6, and 10.0% for propionaldehyde; 3.3, 7.8, 16.0, and 26.0% for butyraldehyde.

Sureshkumar et al. [52] presented the results of performance and emission analyses carried out in an unmodified diesel engine fuelled with Pongamia pinnata methyl ester (PPME) and its blends with diesel. The engine used to carry out the experiments was a single cylinder, four-stroke, water-cooled and constant-speed (1500 rpm) compression ignition engine. Engine tests were conducted to get the comparative measures of brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and emissions such as CO, CO_2, HC, NO_x to evaluate the behaviour of PPME and diesel in varying proportions. For the blends B20 and B40, the BSFC was lower than and equal to that of diesel, respectively, and the BSEC was found less than that of diesel at all loads. However, as the PPME concentration in the blend increased, the BSFC increased at all loads. The BSEC for all the fuels tested increases initially at low loads and at higher load conditions; its value is less than that of diesel for all the blends and more than that of diesel for PPME. The CO concentration was totally absent for the blends of B40 and B60 for all loading conditions and as the PPME concentration in the blend increases above 60%, the presence of CO was observed. However, engine emits more CO for diesel as compared to PPME blends under all loading conditions. The lower percentage of PPME blends emits less amount of CO_2 in comparison with diesel. Blends B40 and B60 emit very low emissions. This was attributed to the fact that biodiesel in general is a low carbon fuel and has a lower elemental carbon to hydrogen ratio than diesel fuel. The hydrocarbon emissions were almost zero for all PPME blends except for B20 where some traces were seen at no load and full load. As the PPME content of the fuel increased, a corresponding reduction in NO_x emission was noted and the reduction was remarkable for B40 and B60. The maximum and minimum amount of NO_x produced were 230 and 48 ppm corresponding to B20 and B60. From the experimental studies, the investigators concluded that blends of PPME with diesel up to 40% by volume (B40) could replace the diesel for diesel engine applications for getting less emissions and better performance and will thus help in achieving energy economy, environmental protection and rural economic development.

Zheng et al [53] compared the performance and emissions of the engine fuelled with soy, Canola and yellow grease derived B100 biodiesel fuels and an ultra-low sulphur diesel fuel under high load engine operating conditions. Conditions and the performance of the test fuels were examined. For the high load, a brake mean effective pressure (BMEP) level of 8 bar was used, representing about 65% of the maximum rated power. The tests were conducted on a naturally-aspirated, four stroke, single cylinder, direct injection diesel engine coupled to a DC motoring dynamometer. In the high load operating condition, the engine-out NO_x emissions were dependent on the fuel cetane number, for the same SOI. The biodiesel fuel with a cetane number similar to the diesel fuel produced higher NO_x emissions than the diesel fuel. The biodiesel fuels with a higher cetane number, however, had comparable NO_x emissions with the diesel fuel. A higher cetane number would result in a shortened ignition delay period thereby allowing less time for the air/fuel mixing before the premixed burning phase. Consequently, a weaker mixture would be generated and burnt during the premixed phase resulting in relatively reduced NO_x formation. Generally the emissions of soot, CO and HC were lower for the engine fuelled with biodiesels.

Banapurmath et al. [54] reported the results of research conducted in a four-stroke, single cylinder, water-cooled, direct injection, compression-ignition (CI) engine using Honge oil and blends of its ester. Experiments were conducted with injection timings of 19, 23 and 27^0 BTDC at various loads and at a constant rated speed of 1500 rev min^{-1}. The performance and emission characteristics of Honge oil and Honge oil methyl ester (HOME) blended with diesel, to produce blends designated B20, B40 and B80, were studied. The brake thermal efficiency with B20 operation was closer to diesel operation. Increasing the proportion of HOME in the blend decreases the thermal efficiency. This decrease was attributed by the investigators to the poor combustion characteristics of the blends due to their relatively high viscosity and poor volatility that overcomes the advantage of the excess oxygen present in the biodiesel. The maximum brake thermal efficiency value observed with HOME operation was 29.51% at 80% load whereas it was 31.25% with diesel. With increasing blend ratio, the exhaust gas temperature slightly increases. This was attributed to the lower calorific value of HOME. The smoke level at maximum power was 78.5 HSU for HOME, 75 HSU for the B20 blend and 84 HSU for the B80 blend and 70 HSU for diesel at full load. The HC emissions were found to be 75, 84 and 65 ppm for B20, HOME and diesel respectively and the CO emissions were 0.26, 0.32 and 0.20% for B20, HOME and diesel respectively. The NO_x emissions for B20, B40, B80 and B100 fuels were measured as 1150, 1066, 1055 and 1070 ppm in comparison with 1250 ppm for diesel operation. Of the HOME blends tested, B20 gave the best performance with reduced emissions. The BTE of the engine with the B20 blend at 80% power output was 30.00 % which is the closest to diesel operation. Hence the investigators recommended B20 blend for existing diesel engines.

Keskin et al. [55] studied the usability of cotton oil soap stock biodiesel-diesel fuel blends as an alternative fuel for diesel engines. The biodiesel used in this study was produced by reacting cotton oil soap-stock with methyl alcohol at determined optimum condition. The cotton oil biodiesel-diesel fuel blends were tested in a single cylinder direct injection diesel engine. There were no noticeable differences in the measured engine power output between diesel fuel and the blends fuels at lower speeds. However, at higher engine speeds, a slight decrease in power output of the engine was obtained with B40 and B60 compared to diesel fuel. Comparing with diesel fuel, increasing of specific fuel consumption with blend fuels ranged from 0% to 10.5%, depending on the amount of biodiesel. The lowest percent heat losses to exhaust were obtained with blend of B20. The results showed that engine thermal efficiency of the engine with B20 increased. However, there were no significant differences in percent heat loss to exhaust of engine between other blend fuels and diesel fuel. Particulate Matter with blend fuels decreased at maximum torque speed by 46.6% depending on the amount of biodiesel. The properties of blend fuels, such as oxygen content, higher cetane number and low levels of sulphur content, improved combustion process. It was concluded based that blends of cotton oil soap stock biodiesel and diesel fuel can be used as alternative fuels in conventional diesel engines without any major changes. It was also stated that high calorific value, high cetane number, low sulphur content and low aromatic content, are advantages of cotton oil soap-stock biodiesel–diesel fuel blends. Moreover, cotton oil soap-stock as raw material is cheaper than other vegetable oils.

Agarwal et al. [56] carried out a study to investigate the performance and emission characteristics of Mahua oil, Rice bran oil and Linseed oil methyl ester (LOME), in a Kirloskar stationary single cylinder, four stroke diesel engine and compare it with mineral diesel. The linseed oil, Mahua oil, Rice bran oil and LOME were blended with diesel in different proportions. Baseline data for diesel fuel was collected. The performance data were analyzed based on the data recorded for BTE, brake-spec ific energy consumption (BSFEC), and smoke density for all fuels. The performance and emission parameter for different fuel blends were found to be very close to diesel. 50% linseed oil blend and 30% Mahua oil blend with diesel showed minimum thermal efficiencies compared to their respective blends. Smoke density and BSFEC were slightly higher for vegetable oil blends compared to diesel. However, BSFEC for all oil blends was found to be lower than diesel. BSFEC was found minimum for 20% biodiesel blend. Also 20% rice bran oil blend showed minimum BSFEC than other blends. However, BSFEC was slightly higher for biodiesel blends than mineral diesel. 20% LOME showed improved smoke emission performance than other blends. However, at lower loads, 100% LOME showed slightly higher smoke density than other blends. Economic analysis was also conducted to find out cost of biodiesel after transesterification. Comparative study of cost for different vegetable oils, biodiesel and mineral diesel showed that cost per unit energy produced is almost similar for all fuels.

Korres et al. [57] made an effort to evaluate JP-5 along with diesel and biodiesel for use in a diesel engine. Naval aviation turbine fuel, JP-5, has been accepted as alternative to JP-8 in the frame of the Single Fuel Policy. In this study, JP-5 was used along with diesel and/or biodiesel fuel on a diesel engine, in order to evaluate its behaviour in the frame of the Single Fuel Policy. The fuels used were typical diesel and JP-5 fuels of the Greek market, satisfying the EN-590 specification for 2005 and the MIL-DTL-5624U specification, respectively, and biodiesel derived from animal fats. The base fuels were tested for compliance to the specifications and then used, alone and in various blends, on a stationary single-cylinder diesel engine. Emissions were measured under various loads, along with the volumetric fuel consumption. The diesel fuel used served as the reference. The addition of biodiesel in the blend caused an increase in NO_x emissions as compared to the reference fuel case, while JP-5 reduced these emissions when used in percentages up to 40% by volume. However, these emissions strongly depend on the engine type and the cycle used for their measurement. Particulate matter (PM) emissions were significantly lowered with the addition of biodiesel, as expected. JP-5 initially reduced PM emissions, but when used in percentage over 60% by volume, JP-5 slightly increased the emissions, probably due to its lower cetane number. However, PM emissions with JP-5 remained lower than diesel fuel emissions. Fuel sulphur content seemed to have an undesirable effect on smoke opacity, as observed by the filter luminosity results. The biodiesel increased fuel consumption due to its chemically bound oxygen content. In comparison with the petroleum derived fuels biodiesels showed about the same consumption results. Overall, JP-5 was found to be an attractive alternative for diesel fuel in the frame of Single Fuel Policy.

Kalam and Masjuki [58] presented the experimental test results of a diesel engine using additive-added Palm biodiesel (it is also known as Palm diesel) obtained from palm oil. The test results obtained are brake power, SFC, exhaust emissions and anti-wear characteristics of fuel's contaminated lubricants. The diesel engine used for this study was Isuzu make, of four cylinder, four stroke, water cooled, indirect injection. The test fuels chosen were (1) 100% conventional diesel fuel (B0) supplied by the Malaysian petroleum company (Petronas), (2) B20 as 20% POD blended with 80% B0 and (3) B20X as B20 with X% additive. 4-Nonyl phenoxy acetic acid (NPAA) (CAS number-3115-49-9) was used as additive in biodiesel fuel. The maximum brake power obtained at 2500rpm was 12.28kW fromB20X fuel followed by 11.93kW (B0) and 11.8kW (B20). They attributed this to the effect of fuel additive in B20 blend which influences the conversion of thermal energy to work or increases the fuel conversion efficiency by improving the fuel ignition and combustion quality. The lowest SFC was obtained from B20X fuel followed by B0 and B20 fuels. The average SFC values all over the speed range were 405, 426.69 and 505.38 g/kWh for B20X, B0 and B20 fuels, respectively. It was found that NO_x concentration decreases with B20X fuel (92ppm), which was lower than B20 (119ppm) and B0(115ppm) fuels. It can be examined that NO_x is produced from high combustion temperature. 1% additive was found to be helpful to reduce combustion temperature by allowing high fuel conversion as compared to B20 fuel. Hence, the additive was effective in B20 fuel. It was also found that among all the fuels, fuel B20X produced the lowest level of CO emissions, which was 0.1%, followed by B20 (0.2%) and B0 (0.35%). 1% additive in biodiesel-blended fuel produced complete combustion as compared to B0 fuel. B20X produced lowest HC emission (29ppm) followed by B20 (34 ppm) and B0 (41ppm). From the lubricant test results, it was found that from 1% to 3% of B20X contaminated into lubricant acts as anti- wear additive by reducing Wear Scar Diameter and the coefficient of friction and increasing Flash Temperature Parameter. Hence, the additive was found to be effective in B20 fuel used in diesel engine.

Karabectus et al. [59] investigated the performance and exhaust emissions of a diesel engine fuelled with diesel fuel and a biodiesel, namely Cottonseed oil methyl ester (COME). COME was prepared using cottonseed oil, methyl alcohol and potassium hydroxide as a catalyst. The fuel properties of COME were determined according to ASTM standard test procedure in Petroleum Research Centre of Middle East Technical University. Tests were carried out at full load conditions in a single cylinder, four-stroke, direct injection diesel engine. Before supplied to the engine, COME was preheated to four different temperatures, namely 30 ^{0}C, 60 ^{0}C, 90 ^{0}C and 120 ^{0}C. Preheating of COME was carried out using fuel heating equipment mounted just upstream of the fuel pump. A resistance controlled by a thermostat was installed around a fuel reservoir. The thermostat was used for keeping the temperature of the COME in the reservoir at the required value by energising or de-energising the resistance. Preheating of the COME caused a considerable decrease in its kinematic viscosity and a slight decrease in its specific gravity, thus causing them to approach the values of diesel fuel. COME preheated to 30 ^{0}C, 60 ^{0}C, 90 ^{0}C and 120 ^{0}C are indicated by COME30, COME60, COME90 and COME120, respectively. The test data were used for evaluating the brake power and BTE together with CO and NO_x emissions. The results revealed that preheating COME up to 90 ^{0}C leads to favourable effects on the BTE and CO emissions but causes higher NO_x emissions. Compared to diesel fuel, the brake power obtained with COME30, COME60 and COME90 were moderately decreased, whereas it was significantly decreased with COME120 because of excessive fuel leakage. A higher BTE was determined with the preheated COME mainly due to its lower heating value and improved combustion compared to diesel fuel. Particularly, COME90 and COME120 yielded with a high improvement in the BTE. The use of preheated COME usually yielded a significant decrease in CO emissions, while NO_x emissions were increased due to higher combustion temperatures caused by preheating and oxygen content of COME. The results suggest that COME preheated up to 90 ^{0}C can be used as a substitute for diesel fuel without any significant modification at the expense of increased NO_x emissions.

Keskin et al. [60] investigated the effect of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission. Tall oil resinic acids were reacted with MgO and MoO_2 stoichiometrically for the production of metal-based fuel additives (combustion catalysts). The metal-based additives were added into tall oil biodiesel (B60) at the rate of 4 μmol/l, 8 μmol/l and 12 μmol/l for preparing test fuels. In general, both the metal-based additives improved flash point, pour point and viscosity of the biodiesel fuel, depending on the rate of additives. The measured SFC of B60 with metal-based additives slightly decreased. The values of SFC obtained with B60–8Mo were lower than the other test fuels. The catalyst effect of metal-based additives and better fuel properties of biodiesel increased the thermal efficiency of the engine by reducing SFC. CO emission of biodiesel fuel decreased with Mg and Mo based additives. In comparison with B60, maximum reduction with Mg and Mo based additives was 36.21% with B60–12Mg at 2600 rpm and 24.12% with B60–12Mo at 2400 rpm, respectively. In general, when compared to Mo-based additive, relatively lower CO emission was measured with Mg-based additive. The CO emissions decreased mainly because of the catalyst effect as stated in the study. At low engine speed, although lower NO_x emissions were measured with B60–8Mg and B60–12Mg, the higher NO_x emissions were recorded with other biodiesel fuels. In addition, in comparison with Mo-based additives, lower CO_2 concentration was measured with Mg-based additives. Due to oxygen content of biodiesel fuels and catalyst effect of the metal-based additives, smoke opacity of biodiesel fuels reduced at all engine speeds when compared with diesel fuel.

Meng et al. [61] studied the impact of biodiesel/diesel blend fuels on aYC6M220G turbo-charge diesel engine & exhaust emissions were evaluated compared with diesel. The biodiesel used was produced from waste cooking oil. The tested results showed that without any modification to diesel engine, under all conditions, the performance of the engine kept normal, and the B20, B50 blend fuels (include 20%, 50% crude biodiesel respectively) led to unsatisfactory emissions while the B'20 blend fuel (include 20% refined biodiesel) significantly reduced emissions. In general, the reference fuel B0 resulted in smaller fuel consumption per unit energy output compared to all other blends fuels which may be, according to the investigators, due to the lower calorific value in the blend fuels. The minimum values of specific fuel consumption for B0, B20 and B50 was 203.4 g/(kWh), 210.7 g/(kWh) and 222.8 g/(kWh) respectively. The emissions of carbon monoxide, unburned hydrocarbons and nitrogen oxide were examined. B20, B50 blend fuels both were inferior to the reference fuel as far as carbon monoxide and unburned hydrocarbons were concerned and better in nitrogen oxide emission.

Banapurmath et al. [62] evaluated the feasibility of popular alternative fuels in the form of Honge oil/Honge oil methyl ester and producer gas as a total replacement for fossil fuels. Experiments were conducted on a single cylinder four-stroke CI engine operated on single and dual fuel modes at three injection timings of 19^0, 23^0 and 27^0 BTDC and three injection pressures of 190, 200 and 210 bar. Earlier, in single fuel mode of operation, optimum conditions in terms of injection timings and injection pressures for Honge oil and Honge oil methyl ester were determined. The results obtained indicated BTE in dual fuel mode of operation to be lesser than single fuel mode of operation at all the injection timings investigated. However, it was observed that the BTE improved marginally when the injection timing was advanced for both Honge oil and Honge oil methyl ester. The BTE with dual fuel operation at injection timings of 19^0, 23^0 and 27^0 BTDC is 17.25%, 18.25% and 19.00%, respectively, as compared to 28.5%, 27% and 26% for neat Honge oil operation. EGT is found to be higher for dual fuel mode as compared to single fuel mode at all fuel injection timings. The smoke emission for Honge oil- producer gas was found to be more than producer gas-diesel oil. This was due to comparatively higher viscosity of Honge oil. However, with producer gas-Honge oil methyl ester higher brake thermal efficiency and reduced emissions were obtained. With dual fuel operation, smoke and NO_x emissions were considerably reduced with increase in CO emissions. On the whole, it is seen that operation of the engine is smooth on Honge oil–producer gas, Honge oil methyl ester–producer gas dual fuel operation.

Honge oil producer gas results in a slightly reduced thermal efficiency and increased smoke, HC and CO levels.

Nadar and Reddy [63] modified a single cylinder, four stroke, diesel engine to work in dual fuel mode. To study the feasibility of using methyl ester of Mahua oil (MEMO) as pilot fuel, it was used as pilot fuel and liquefied petroleum gas was used as primary fuel. In dual fuel mode, pilot fuel quantity and injector opening pressure were varied as they affected the performance and emissions of the engine. The values of injector opening pressure selected were 180, 200 and 220 bar and pilot fuel quantity were 5, 6, 11 and 7.22 mg per cycle. The diesel engine was modified to work in the dual fuel mode by attaching an LPG line to the intake manifold. The pilot MEMO flow rate and LPG flow rate were varied by adjusting the fuel injection pump and the flow control valve, respectively. The pilot fuel quantity of 5 mg per cycle resulted in higher brake thermal efficiency at the injector opening pressure of 200 bar. The injector opening pressure of 180 bar resulted in EGT. The reason for this was stated that due to injection of pilot fuel at low pressure a higher ignition delay resulted in slow combustion of the fuel. This slow combustion further resulted in higher combustion temperature and hence caused higher EGT. It was observed that the injector opening pressure of 200 bar resulted in lower CO emission at the pilot fuel quantity of 5 mg per cycle due to complete combustion of fuel. The injector opening pressure of 200 bar resulted in lower HC emission. The lowest HC emission was observed between the pilot fuel quantity of 5 mg per cycle and 6.11 mg per cycle. The injector opening pressure of 220 bar resulted in lower NO_x emission. This could be due to the poor combustion of the fuel which results in lower combustion temperature and hence lower NO_x emission. It was also found that the injector opening pressure of 200 bar results in lower smoke emission at the pilot fuel quantity of 5 mg per cycle. Higher heat content of LPG, higher combustion temperature, extended duration of combustion and rapid flame propagations were the reasons stated for reduced smoke level. From the experimental results it was concluded that MEMO can be used as a substitute for diesel in dual fuel engine with the pilot fuel quantity of 5 mg per cycle and at the injector opening pressure of 200 bar.

Devan and Mahalakshmi [64] evaluated experimentally the performance and emissions of a direct injection (DI) diesel engine using Poon oil-based bio-diesels of B20 and B40 blends. The reductions in smoke, hydrocarbon and CO emissions were found to reduce but the NO_X was found to slightly increase. B40 blend was investigated to be better performance wise. This is due to the fact that ignition delay is shorter because of higher cetane number, the combustion was complete and cleaner since the fuel contains oxygen in its molecular structure. Smoke, percentage is less with bio-diesel compared to neat oil due to better combustion. Air fuel ratio is higher for bio-diesels. Esterified oils were better in their heat release characteristics as compared to neat oil. Diesel has slightly higher heat release rate and higher peak pressure in the cylinder during combustion.

Anand and Kannan [65] conducted experimental study of performance and emissions characteristics of a variable compression ratio (VCR) diesel engine running at constant speed on cotton seed oil based bio diesel (COME) in blend proportion of 5% to 20% with diesel. Experimental investigation revealed that higher BTE and lower SFC were observed when biodiesel proportions were less and compression ratios were 15 and 17. At 15: 1 compression ratio (CR), the BSFC is increased by 2.5% and 4.92% for the B5 and B20 blends. At 17:1 CR, it is increased by 3.5% for both the B5 and B20 blends, whereas at 19:1 CR, the B20 blend suggests slightly better fuel economy. The maximum BTE varied between 27.37-29.28% for COME-diesel blends and 26.65-27.92% for Diesel fuel. Higher the blend proportion, a higher CR was required to give similar performance hence they concluded that bio-diesel running needed a higher CR. NO_X emissions were higher as the CR increased. The maximum NO_x emissions were found to be 205 ppm at a CR of 17. The emission of CO and CO_2 were slightly higher for lower blends. The emission of unburned hydrocarbons HC for all fuels were low, 15–80 ppm, showing slightly milder values for COME-diesel blends compared with diesel fuel. All bio-diesel blends tested revealed that they can be safely used in the engine requiring no hardware modifications as such.

Jindal et al. [66] conducted an experimental investigation on the effect of CR and IP in a DI diesel engine running on Jatropha methyl ester. The study was targeted at finding the suitability of bio-diesel with respect to the standard design parameters of diesel engine. Results revealed that increase in CR up to 18.5 improves the performance of bio-diesel as far as BSFC and BTE were concerned as against diesel at preset CR of 17.5 during the trials three injection pressure of 150, 200 and 250 bar were considered. The BSFC was lowest at 200 bar for 50% load and at 250 bar for higher loads where as it was high at 150 bar. This can be attributed to more efficient utilization fuel at higher IP because of better atomization and slight delay in admission of fuel and hence lesser fuel going into the engine cylinder. There is 10% improvement over the standard setting of 17.5 CR/210

IP. BTE increases by about 8.9% with load as the losses encountered are less at higher loads. At CR of 18, there is 5.5% increase in BTE because of better combustion and higher lubricity. Higher compression ratio generally ensures better combustion due to proper atomization and higher surface area available for proper fuel air mixing. Emissions from engine like particulate hydrocarbon, NO_X, EGT and smoke opacity are found lower compared to diesel with slight increase observed in CO and CO_2 emissions. NO_X emissions were found slightly higher at 250 bar and higher CRs because of higher exhaust temperature. All comparisons are made for bio-diesel against base line data of diesel.

Bajpai et al. [67] undertook an experimental study to assess the feasibility of blending Karanja vegetable oil with diesel oil and utilization in a DI diesel engine. Pre heating of oil and blending with diesel was found to reduce the viscosity and with higher flash point, it was safe to store. Engine operation for short duration test studies were satisfactory requiring no major engine hardware modification and can suitably substitute petro-diesel. Performances were comparable and emissions were less for entire range of operations. Self lubricity and free oxygen content of the fuel suggested that, Karanja as an optimum test fuel with slight modification in injection timing and duration to offset its higher viscosity effect.

Banapurmath and Tewari [68] investigated at the prospects of using a dual fuel mode with producer gas and bio-diesel combination towards reducing petro-diesel consumption by CI engine. They suggest the use of non edible oil esters application to save the domestic food requirement. In this context, Honge oil methyl ester was used. Also vegetable oil based bio-diesel has higher smoke emission but duel fuel operation with producer gas/ biodiesel could reduce this problem with improved performance. This requires the use of certain modification in the form of a gas carburettor in the engine hardware. This would improve the performance due to higher calorific value and reduced viscosity. The BTE values of 24.25%, 22.25% and 23% were obtained with producer gas–diesel, producer gas–Honge oil and producer gas–Honge oil methyl ester, respectively. Smoke and NO_X emissions were lower whereas CO and HC emissions were considerably higher due to higher carbon content of bio-gas. Nitrogen oxide emissions in dual fuel mode of operation were 130 ppm, 195 ppm and 175 ppm with diesel, Honge oil and HOME as injected fuel, respectively.

Kandasamy and Thangavelu [69] investigated on the performance of diesel engine using various bio fuels. In this study the bio fuels were blended with diesel and preheated before it was injected into the cylinder. The preheating ensures the enhancement of combustion efficiency and the overall performance of the engine. The investigators concluded that the highest engine efficiency was obtained for the B60 of Pongamia oil and also that the efficiency increased with increase in the temperature. For the rice bran oil, the variation in the engine efficiency was very minimum with change in temperature and the performance of the engine was found to be good for the B40 blend. However the overall performance of the engine was found to be good when the oil and diesel blend is supplied to the cylinder after pre heating.

Baiju et al [70] investigated the scope of utilizing biodiesel developed from both the methyl as well as ethyl alcohol route (methyl and ethyl ester) from Karanja oil as an alternative to diesel fuel. The physical and chemical properties of ethyl esters were comparable with that of methyl esters. B20 of Karanja Oil Ethyl Ester (KOEE) showed minimum efficiency. The low efficiency obtained might be due to low volatility, slightly higher viscosity and higher density of the ethyl ester of Karanja oil, which affected mixture formation of the fuel and thus leads to slow combustion. At 100% load, B20 Karanja Oil Methyl Ester (KOME) showed the lowest fuel consumption. According to them, it could be due to the fact that engine consumes more fuel with diesel-biodiesel blend fuels than with neat diesel fuel to develop the same power output (due to the lower calorific value of diesel-biodiesel blend fuel). Smoke is lower for B100KOME for all loads. This was due to the complete combustion of KOME due to the presence of more oxygen. Smoke emission from ethyl ester was found to be more than that of methyl ester. Methyl esters emitted less CO compared to ethyl esters. It was observed that the enrichment of oxygen owing to biodiesel addition resulted in better combustion. Among the esters, ethyl esters emitted more NO_x than methyl esters. This might be due to higher bulk modulus of ethyl ester than methyl ester.

Haldar et al [71] studied the performance and emission characteristics of Putranjiva roxburghii. In the Tropic of Cancer, these plants are abundantly available. The investigators observed that million tons of seeds of Putranjiva oil go a waste annually which villagers in remote areas can use in pure form or blended with diesel oil to operate engines for running irrigation pumps, grinding mills or straw choppers for cattle feed for shorter duration at the time of fuel crisis or emergency period. In this study, the Ricardo Variable Compression Diesel Engine was run with 10%, 20%, 30% and 40% blends of pure Putranjiva oil with diesel at different loads (0– 2.7 kW), and different injection timings (45^0, 40^0, 35^0 CA BTDC) at constant compression ratio 20:1. It was found that cetane number of Putranjiva oil is less than diesel which meant that ignition timing is crucial for better combustion and hence improves the engine performance and emissions. It appeared that Putranjiva oil blends yield better in performance at 45^0 CA BTDC injection timing in comparison to 40^0 CA BTDC timing for diesel. The volatile nature of Putranjiva oil increases the hydrocarbon emission in exhaust gas.

Mani and Nagarajan [72] used waste plastic oil as fuel in diesel engine. The properties of waste plastic oil was compared with the petroleum products and found that it can also be used as fuel in compression ignition engines. They studied the influence of injection timing on the performance and emission characteristics of a single cylinder, four stroke, direct injection diesel engine using waste plastic oil as a fuel. Tests were performed at four injection timings (23°,20°,17° and 14° before top dead centre -BTDC). When compared to the standard injection timing of 23° BTDC, the retarded injection timing of 14° BTDC resulted in decreased oxides of nitrogen, carbon monoxide and unburned hydrocarbon while the brake thermal efficiency, carbon dioxide and smoke increased under all the test conditions.

Haldar et al. [73] investigated vegetable oils of Putranjiva, Jatropha and Karanja to find out the most suitable alternative diesel by a chemical processing. These vegetable oils were subjected to degumming in order to improve their properties by removing impurities (gum particles). In degumming process, the vegetable oil to be degummed was mixed with concentrated acid and was vigorously stirred for a few minutes. The mixture was kept for a week so that reaction gets completed and gum particles settle down. The gum can be used as a soil fertilizer and the degummed oil was used after washing it thrice with acid to remove the remaining gum. Degumming is an easy, simple and less expensive process than transesterification where reduction of vegetable oil is little. In this study, Putranjiva vegetable oil was used in a diesel engine for the first time. It was found that out of the three non edible oils tested, Jatropha yields best performance and emission at high loads. The emission levels of CO, CO_2, NO_x, HC, smoke and particulates for Jatropha were encouraging. The parameters varied during experimentation were injection timing and brake power. The experiments were conducted on Ricardo Variable Compression engine using 10%, 20%, 30% and 40% blends of degummed Karanja, Jatropha and Putranjiva oils with diesel. It was found that the oils of Karanja, Jatropha and Putranjiva gave more efficiency at 45^0 BTDC timing than diesel and at 40^0 BTDC timing diesel gives more. The reason stated was less cetane numbers for straight vegetable oils which demanded ignition timing to be more for better combustion. The BSFC and BTE of the engine were satisfactory for 29% blends but blends above 20% did not give effective performance due to their high viscosity. The non edible oils gave lesser emissions due to their higher ignition temperature and better combustion compared to diesel. Overall, it was concluded in this study that any diesel engine used for agricultural purpose can be run with 20% blend of degummed vegetable oil and diesel.

Bhale et al. [74] studied the performance and emission with ethanol blended Mahua biodiesel fuel and ethanol-diesel blended Mahua biodiesel fuel. The tests were conducted on a Kirloskar TV1 four stroke, compression ignition, water cooled, single cylinder engine at the rated speed of 1500 rpm at various loads. The Brake Mean Effective Pressure (BMEP) was varied from 0 to 650 kPa for each blend and observations were taken. The test fuels considered were Mahua methyl ester (MME), MME with 20% ethanol (MME E20), MME with 10% ethanol (MME E10) and MME with 10% diesel and 10% ethanol (MME E10 D10). A considerable reduction in emission was obtained. A 20 volume % ethanol blending into MME achieved improved combustion with reduction in CO by almost 50% on an average without affecting the thermal efficiency. The NO_x emission level was highest for MME. However, with 20% (by volume) ethanol blended MME, it was the lowest. It was stated that low NO_x level was mainly because of the high latent heat of ethanol which reduced the overall combustion temperature which is one of the key parameter for NO_x formation. Smoke emissions from diesel combustion of the MME/ethanol blended fuel decreased strongly with increasing percentage of ethanol in MME. The smoke reduction was attributed to an improved fuel-air mixing by an increased ignition delay due to the lower cetane number as a result of the ethanol addition and also to an increase in the oxygen content in the blended fuel. The quite low boiling point of ethanol also promotes the atomization of the fuel spray and reduces soot by a flash boiling effect. Ethanol blended biodiesel is totally a renewable, viable alternative fuel for improved cold flow behaviour and better emission characteristics without affecting the engine performance.

Nagaprasad et al [75] conducted experiments to determine the performance of castor non-edible vegetable oil and its blend with diesel on a single cylinder, 4 stroke, naturally aspirated, direct injection, water cooled, eddy current dynamometer Kirloskar Diesel Engine at 1500 rpm for variable loads. Initially, neat castor oil and their blends were chosen. The BTE, BSFC of castor oil were found to be 33.45% lower and 34.76% higher compared to those of diesel. This was attributed to higher viscosity and lower calorific value of the fuel. However at rated load, the neat castor oil emissions viz. CO, UHC, smoke were 56.41%, 20.27%, 31.32% respectively higher and NO_x were 44% lower compared to those of diesel. This was attributed to incomplete combustion of the fuel and delay in the ignition process. The Exhaust gas temperature (E.T) of 25% blend of castor oil has lower values compared with all other blends and is well comparable with diesel. The E.T of all blends and diesel increased with increase of operating loads. The 25% blend of castor oil has higher performance than other blends due to reduction in exhaust gas temperature. From the analysis, it was observed that 25% of neat Castor oil mixed with 75% of diesel was the best suited blend for diesel engine without any engine modifications. It was concluded that castor non-edible oil can be used as an alternate to diesel, which is of low cost. The usage of neat bio-diesel will have a great impact in reducing the dependency of India on oil imports, they opined.

Karabectas [76] investigated the effect of turbocharger on the performance and emissions of a diesel engine fuelled with rapeseed oil methyl ester. The performance of the engine was measured in terms of brake power, torque, BSFC and BTE and the emissions measured were CO and NO_x. A naturally aspirated (NA) four stroke direct injection diesel engine was used to carry out the experiments. The experiments were carried out at full load and at speeds between 1200 rpm and 2400 rpm with intervals of 200 rpm. To record the second set of readings, a turbocharger (TU) with boost pressure of 0.7 bar was installed on the engine and readings were recorded at same conditions as done in the earlier case. The brake power and torque of the engine with diesel as fuel were higher than those with biodiesel for both NA and TU operations. However, the use of turbocharger caused considerable increase in brake power and torque with biodiesel when compared to diesel fuel. Also, the values of brake power and torque in the cases of diesel fuel and biodiesel approached each other in TU operation. Under both NA and TU operating conditions, biodiesel showed slightly higher BSFC in comparison to diesel fuel. According to the investigator, this was due to higher fuel density and lower calorific value of biodiesel. It was also found that BSFC decreased in case of TU operation compared to NA operation. The BTE for biodiesel was higher in case of NA operation while in TU operation, it improved further compared to the BTE when engine was fuelled with diesel fuel. NO_x emissions were higher with biodiesel than that with diesel, while CO emissions were less with biodiesels. The higher oxygen content in biodiesels was stated as the reason for higher NO_x emissions. Better combustion of biodiesel due to its higher cetane number and oxygen content resulted in less CO emissions. In the case of TU operation a noticeable increase in NO_x emissions was observed for both diesel and biodiesel. The TU operation with biodiesel resulted in higher ratio of decrease in CO emissions compared to diesel fuel. Overall, it was concluded that the use of biodiesel improves the performance and exhaust emissions of the turbocharged engine better compared with the use of diesel fuel.

Qi et al. [77] conducted an experimental study on the performance characteristics of a direct injection engine fueled with biodiesel/diesel blends. In this study, the biodiesel produced from soybean crude oil was prepared by a method of alkaline-catalyzed transesterification. The effects of biodiesel addition to diesel fuel on the performance, emissions and combustion characteristics of a naturally aspirated DI compression ignition engine were examined. Biodiesel has different properties from diesel fuel. A minor increase in BSFC and decrease in BTE for biodiesel and its blends were observed compared with diesel fuel. The significant improvement in reduction of CO and smoke were found for biodiesel and its blends at high engine loads. HC had no evident variation for all tested fuels. NO_x were slightly higher for biodiesel and its blends. Biodiesel and its blends exhibited similar combustion stages to that of diesel fuel. The use of transesterified soybean crude oil can be partially substituted for the diesel fuel at most operating conditions in terms of the performance parameters and emissions without any engine modification.

Panwar et al. [78] conducted a study for Performance evaluation of a diesel engine fuelled with methyl ester of castor seed oil. In this investigation, castor methyl ester (CME) was prepared by transesterification using potassium hydroxide (KOH) as catalyst and was used in four stroke, single cylinder variable compression ratio type diesel engine. Tests were carried out at a rated speed of 1500 rpm at different loads. Straight vegetable oils pose operational and durability problems when subjected to long term usages in diesel engines. These problems were attributed to high viscosity, low volatility and polyunsaturated character of vegetable oils. The process of transesterification was found to be an effective method of reducing vegetable oil viscosity and eliminating operational and durability problems. The important properties of methyl ester of castor oil were compared with diesel fuel. The engine performance was analyzed with different blends of biodiesel and was compared with mineral diesel. It was concluded that the lower blends of biodiesel increased the break thermal efficiency and reduced the fuel consumption. The exhaust gas temperature increased with increasing biodiesel concentration indicating that Biodiesel is a viable alternative to diesel.

Aydin and Ilkilic [79] used ethanol as an additive to research the possible use of higher percentages of biodiesel in an unmodified diesel engine. Commercial diesel fuel (DF), 20% biodiesel and 80% diesel fuel (B20), and 80% biodiesel and 20% ethanol (BE20), were used in a single cylinder, four strokes direct injection diesel engine. The effect of test fuels on engine torque, power, brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, and CO, CO_2, NO_x and SO_2 emissions were investigated. The engine torque that obtained for BE20 was higher than both those obtained for diesel and B20 fuels. Average increase of torque values for BE20 was 1.2% and 1.3% when compared to diesel fuel and B20, respectively. The obtained powers for DF and BE20 were almost similar, however the power obtained from B20 was lower than that of other fuels. According to the authors, the higher values of viscosity, density and higher cetane number of B20 were responsible for this power reduction. Average brake-specific fuel consumption for usage of B20 was 22.32% higher than that of diesel fuel and 20.13% higher than that of BE20. It was observed that brake thermal efficiency was 31.71% at 2500 rpm for BE20, while those of DF and B20 were 28.15% and 25.95% respectively. The EGT with BE20 was higher when compared to those of diesel and B20 fuels. The main reason for large difference between BE20 and diesel fuel was stated as the improved combustion of BE20 due to the ethanol added to biodiesel. The NO_x emissions were slightly increased with the use of both biodiesel–ethanol blend and standard diesel fuel with respect to those of the biodiesel–diesel blend. But as far as CO_2 emissions are concerned, a drastic decrease was obtained for B20 fuel when compared with those of both diesel and BE20 fuels. For B20 the average CO_2 decrease was about 67% and 67.5% when compared to diesel and BE20 fuels, respectively. The CO and SO_2 emissions were reduced with the use of both biodiesel–ethanol and biodiesel–diesel blends with respect to those of the neat diesel fuel. The main conclusion derived by this research is that the use of ethanol with biodiesel can potentially remove serious problem revealed with the use of high percentages of biodiesel in operation of unmodified diesel engines.

Sayin and Gumus [80] investigated the influence of compression ratio (CR) and injection parameters such injection timing (IT) and injection pressure (IP) on the performance and emissions of a Direct Injection diesel engine using biodiesel blended-diesel fuel. The increased IP gave the better results for BSFC, BSEC and BTE. Finer breakup of fuel droplets obtained with increased IP provide more surface area and better mixing with air and this effect improved combustion. It was also found that by increasing CR density of air charge was enhanced in the cylinder. The more density and the higher angles of spray cone resulted in increase of amount of air entrainment in the spray. Enough air in the fuel spray contributes to the completion of combustion.

Zhu et al. [81] conducted a study using diesel fuel, biodiesel and biodiesel-ethanol (BE) blends on a 4-cylinder direct-injection diesel engine to investigate the performance and emission characteristics of the engine under five engine loads at the maximum torque condition and engine speed of 1800 rpm. In comparison with Euro V diesel fuel, the biodiesel and BE blends have higher brake thermal efficiency. On the whole, compared with Euro V diesel fuel, the BE blends led to reduction of both NO_x and particulate emissions of the diesel engine. The degree of reduction of NO_x and particulate matter reductions increased with increase in ethanol in the blends. With high percentage of ethanol in the BE blends, the HC, CO emissions could increase. But the use of BE5 could reduce the HC and CO emissions as well.

The studies conducted on performance and emissions of biodiesels from 2000 to 2011 are shown in Table 2.4 in a chronological order. The studies are categorized into the thermal performance, emission characteristics and both the thermal performance & emissions characteristics. Also, the type of fuels used for the respective studies are identified.

Table 2.4 Summary of Studies Based on Thermal Performance and Emission Characteristics

Sr. No	Investigators	Year	Fuel	Type of study (*TP/EC/ TP&EC)	Remarks
1	Mc Donnel et al.	2000	Semi-Refined rapeseed oil	TP	The use of rapeseed oil over a longer period of time was found to shorten the injector life due to carbon build up even though there was no wear on the engine components or lubricating oil contamination.
2	Kalam and Masjuki	2002	Palm oil biodiesel(POD) and its	EC	It was stated that POD blends with corrosion inhibitor additive could be

			blends with diesel		effective as alternative fuels for diesel engines because they reduce emissions levels such as those of NO_x, CO and HC.
3	Senthil Kumar et al.	2003	Jatropha oil with methanol	TP & EC	Jatropha oil can be used as fuel in diesel engines directly and by blending it with methanol. Also use of methyl ester of Jatropha oil and dual fuel operation with methanol induction gives better performance and reduced smoke emissions than blend.
4	Raheman and Phadatare	2004	Karanja biodiesel	TP & EC	A 26% reduction in NOx was obtained for biodiesel and its blends as compared to diesel. CO and smoke was less for Karanja. BTE was less and BSFC was higher for biodiesel.
5	Carraretto et al.	2004	Commercial biodiesel	TP & EC	By reducing the injection angle with respect to nominal injection advance operation, power and torque were found to be increased up to almost the levels of pure diesel oil while SFC was reduced. CO emissions were reduced but NO_x were increased with the use of biodiesel.
6	Nwafor	2004	Rapeseed oil	EC	The investigator stated that less cone angle of the fuel spray, less viscosity and efficient combustion had a considerable effect on CO_2 emissions.
7	Pradeep and Sharma	2005	Rubber seed oil and its blends with diesel	TP & EC	BTE was found lower for bio-diesel blends compare to diesel.
8	Ramadhas et al	2005	Methyl esters of rubber seed oil	TP & EC	It was found that biodiesel fuelled engines emit more NO_x as compared to that of diesel fuelled engines. For biodiesel, the BSFC was found to be higher than that of diesel
9	Usta	2005	Tobacco seed oil methyl ester	TP & EC	It was observed that the turbocharged diesel engine used in the experiments supplied more air at the higher speeds resulting in an increase of turbulence intensity in the combustion chamber. This enabled more complete combustion. Therefore, the beneficial effect of TSOME as an oxygenated fuel was partially lost at high speeds.
10	Sukumar Puhan et al.	2005	Mahua oil methyl ester	TP	It was found that BSFC for MOME is higher than diesel. This according to the investigators was due to the fact that esters have lower heating value compared to diesel so more ester-based fuel is needed to maintain constant power output.
11	Duran et al	2005	Palmitic, oleic and linoleic acids methyl esters	EC	The amount of palmitic acid methyl ester in fuels is the main factor affecting the particulate matter emissions.
12	Labeckas and Slavinskas	2005	Rapeseed methyl ester and its blends with diesel	TP & EC	For the engine fuelled with rapeseed methyl ester NO_x emissions were higher than diesel fuelled engine
13	Usta et al.	2005	Hazelnut soap	TP & EC	The noise measurements were taken 1

			stock/waste sunflower oil mixture		m away from the engine in the engine room by using a sound level meter. The biodiesel addition slightly decreased the noise. The reduction amount was less than 1 dB in the range of engine speeds tested.
14	Narayana Reddy and Ramesh	2006	Jatropha oil	TP & EC	The BTE increased, HC and smoke emissions reduced with advanced injection timing and increased IP whereas enhancing the swirl had only a small effect on emissions.
15	Yoshimoto	2006	Rapeseed oil	TP & EC	It was found that the performance was improved with rapeseed oil slightly increased emissions of CO and NO_x with knock free combustion
16	Reyes and Sepulveda	2006	Salmon oil biodiesel	TP & EC	It was observed that the maximum power slightly decreased when percentage of crude biodiesel was increased in the fuel blend. Particulate material emission tests were carried out by measuring opacity of the exhaust gases. 100% of refined biodiesel permits reduction of up to 50% of particulate emission and non critical 3.5% of loss in power with a very good specific fuel consumption.
17	Li and Lin	2006	Commercial Biodiesel produced using peroxidation process	TP &EC	They used a biodiesel produced using peroxidation process which was capable of effectively improving fuel properties and reducing the emission pollution of biodiesel.
18	Crookes et al.	2006	Biogas containing carbon dioxide, simulated biogas, commercially available seed oil and rape-seed methyl ester	EC	The oxides nitrogen were less for biogas fuelled engine while unburnt hydrocarbons were increased compared to natural gas fuelled engine.
19	Rakopoulus et al.	2006	Cottonseed oil, soybean oil, sunflower oil and their corresponding methyl esters as well as methyl esters of rapeseed oil, palm oil, corn oil and olive kernel oil	TP & EC	The smoke intensity was significantly reduced with the use of biodiesel blends with respect to that of neat diesel and this reduction was found to be higher with higher percentage of bio-diesels in the blend.
20	D. Dwivedi et al	2006	Commercial Biodiesel	EC	Samples of particulate were collected using a partial flow dilution tunnel for both fuels. Collected particulate samples were analyzed for their metal contents. Metals like Cd, Pb, Na, and Ni in particulate of B20 exhaust were lower than those in the exhaust of mineral diesel.
21	Pereira and Oliveira	2007	Soybean bio-diesel	EC	It was observed that the emission of CO, HC and SO_X decrease and temperature of exhaust gases and the emissions of NO and NO_X were comparable to or less than that of diesel.

22	Altiparmak et al.	2007	Tall oil methyl ester–diesel fuel blends	TP & EC	It was concluded that blended fuels can be used without any modifications in diesel engines. With the use of Tall oil methyl ester–diesel fuel blends decreasing CO emissions were decreased up to 38.9%.
23	Sahoo et al	2007	Polanga oil based methyl esters	TP & EC	The performance of biodiesel-fuelled engine was marginally better than the diesel-fuelled engine in terms of thermal efficiency, brake specific energy consumption, smoke opacity, and exhaust emissions including NO_x emission for entire range of operations.
24	Karthikeyan and Mahalakshmi	2007	Turpentine oil	TP & EC	It was found that all performance and emission parameters of turpentine, except volumetric efficiency, were better than those of diesel fuel.
25	Raheman and Ghadge	2007	Mahua biodiesel and its blends with diesel	TP & EC	From the findings of this study, it was concluded that pure biodiesel could be safely blended with diesel up to 20% without significantly affecting the engine performance (BSFC, BTE, EGT) and emissions (Smoke, CO and NO_x) and thus could be a suitable alternative fuel for diesel.
26	Nazafi et al.	2007	Waste vegetable cooking oil methyl ester and its blends with diesel	TP & EC	By adding 20% of waste vegetable oil methyl ester, it was noticed that the maximum power and torque increased by 2.7 and 2.9% respectively, also the concentration of the CO and HC emissions have significantly decreased when biodiesel was used.
27	Raheman and Ghadge	2008	Mahua oil biodiesel	TP & EC	Based on the results of this study it was concluded that, the performance of bio-diesel would be similar to diesel at higher CRs and advanced injection timings since bio-diesel is slightly more viscous.
28	Roskilly and Nanda	2008	Bio-diesel from recycled cooking oil	TP & EC	This analysis of the performance and exhaust emission indicate that performance was comparable to that of diesel with an increase in rate of fuel consumption with a reduction in NO_x and CO emissions acting as contributors to greener environment.
29	Ashok and Saravanan	2008	Blends of diesel and ethanol	TP & EC	There was an increase of 3.45% efficiency of the blended fuel when compared with the sole diesel fuel. Specific fuel consumption was better for the ratio of 90/10 (Diesel / Ethanol) when compared with sole diesel fuel.
30	Hasimoglu et al.	2008	Sunflower oil based biodiesel	TP	In this experimental study, they used a turbo charged direct injection (DI) diesel engine converted to a LHR engine with thermal barrier coating. The results of this study indicated that the SFC and BTE were improved and the EGT was increased
31	Banapurmath et	2008	Methyl esters of	TP & EC	Engine performed better with sesame

	al		Honge, Jatropha curcas and sesame oils		oil bio-diesel as compared to the other two in terms of thermal efficiency, emission and combustion study.
32	Velimir and Petrovic	2008	Commercial biodiesel	EC	This study presents information on defining the best procedure and methodology for measurement of diesel engine particulate emissions.
33	Utlu and Kocak	2008	Waste frying oil methyl ester (WFOME)	TP & EC	It was stated that lower engine power obtained for WFOME could be due to fuel flow problems, as higher density, higher viscosity, and decreasing combustion efficiency as bad fuel injection may lead to reduced atomization and lower thermal efficiency than diesel fuel.
34	Ballesteros et al.	2008	Sunflower oil biodiesel	EC	Total HC emissions were determined in a regulated emissions bench from environment equipped with a flame ionization detector (FID) which, in addition to the total HC, also measures the amount of methane.
35	Gumus	2008	Hazelnut Oil Methyl Ester	TP & EC	When HOME concentration is increased (B50, B100), the viscosity of blends increased even more and as a result of this, the EGT of blends were lower than EGT of diesel fuel due to more deterioration of combustion and oxidizing of more fuel.
36	Kegl and Pehan	2008	Rapeseed oil biodiesel	EC	It was found that for biodiesel spray angle was narrower and the penetration length was larger. This was due to low fuel vaporization, worse atomization, and higher injection pressure of biodiesel
37	Altun et al.	2008	Sesame oil blended with diesel	EC	It was seen that the blended fuel emitted low CO values and slightly low NO_x values when compared with an ordinary diesel fuel.
38	Correa and Arbilla	2008	Commercial biodiesel	EC	In all biodiesel blends, it was found that total carbonyls emissions were higher at lower speeds than at higher speeds.
39	Sureshkumar et al.	2008	Karanja biodiesel	TP & EC	The investigators concluded that blends of PPME with diesel up to 40% by volume (B40) could replace the diesel for diesel engine applications for getting less emissions and better performance and will thus help in achieving energy economy, environmental protection and rural economic development.
40	Zheng et al	2008	Soy, Canola and yellow grease derived biodiesel fuels	TP & EC	The biodiesel fuel with a cetane number similar to the diesel fuel produced higher NO_x emissions than the diesel fuel. The biodiesel fuels with a higher cetane number, however, had comparable NO_x emissions with the diesel fuel.
41	Banapurmath et	2008	Honge oil, its methyl	TP & EC	The BTE of the engine with the B20

	al		ester and its blends with diesel		blend at 80% power output was 30.00 % which is the closest to diesel operation. Hence the investigators recommended B20 blend for existing diesel engines.
42	Keskin et al.	2008	Cotton oil soap stock biodiesel-diesel fuel blends	TP	It was concluded that blends of cotton oil soapstock biodiesel and diesel fuel can be used as alternative fuels in conventional diesel engines without any major changes. It was also stated that high calorific value, high cetane number, low sulphur content and low aromatic content, are advantages of cotton oil soap-stock biodiesel–diesel fuel blends.
43	Agarwal et al.	2008	Linseed oil, Mahua oil, rice bran oil and linseed oil methyl ester blended with diesel	TP & EC	50% linseed oil blend and 30% Mahua oil blend with diesel showed minimum thermal efficiencies compared to their respective blends. Smoke density and BSFEC were slightly higher for vegetable oil blends compared to diesel.
44	Korres et al.	2008	Naval aviation turbine fuel, JP-5	EC	JP-5 initially reduced PM emissions, but when used in percentage over 60% by volume, JP-5 slightly increased the emissions, probably due to its lower cetane number.
45	Kalam and Masjuki	2008	Palm biodiesel with 4-Nonyl phenoxy acetic acid as additive	TP & EC	1% additive was found to be helpful to reduce combustion temperature by allowing high fuel conversion as compared to B20 fuel.
46	Karabectus et al.	2008	Cottonseed oil methyl ester (COME)	TP & EC	The use of preheated COME usually yielded a significant decrease in CO emissions, while NO_x emissions were increased due to higher combustion temperatures caused by preheating and oxygen content of COME
47	Keskin et al.	2008	Tall oil biodiesel with metal based (Mg and Mo) additives	TP & EC	Due to oxygen content of biodiesel fuels and catalyst effect of the metal-based additives, smoke opacity of biodiesel fuels reduced at all engine speeds when compared with diesel fuel.
48	Meng et al.	2008	Waste cooking oil biodiesel	TP & EC	The tested results showed that without any modification to diesel engine, under all conditions, the performance of the engine kept normal, and the B20, B50 blend fuels (include 20%, 50% crude biodiesel respectively) led to unsatisfactory emissions while the B'20 blend fuel (include 20% refined biodiesel) significantly reduced emissions.
49	Banapurmath et al.	2008	Karanja oil and its methyl ester with producer gas	TP & EC	It was observed that the Brake thermal efficiency improved marginally when the injection timing was advanced for both Karanja oil and Karanja oil methyl ester. The operation of the engine is smooth on Karanja oil–producer gas, Karanja oil methyl ester–producer gas dual fuel

					operation. Karanja oil producer gas results in a slightly reduced thermal efficiency and increased smoke, HC and CO levels.
50	Nadar and Reddy	2008	Mahua oil methyl ester (MEMO) and liquefied petroleum gas (LPG)	EC	The diesel engine was modified to work in the dual fuel mode by attaching an LPG line to the intake manifold. The pilot MEMO flow rate and LPG flow rate were varied by adjusting the fuel injection pump and the flow control valve, respectively. From the experimental results it was concluded that MEMO can be used as a substitute for diesel in dual fuel engine with the pilot fuel quantity of 5 mg per cycle and at the injector opening pressure of 200 bar.
51	Devan and Mahalakshmi	2009	Poon oil-based bio-diesel and its blends with diesel	EC	The smoke, hydrocarbon and CO emissions were found to reduce but the NO_x was found to slightly increase for biodiesel blends.
52	Anand and Kannan	2009	Cottonseed oil methyl ester	TP & EC	At compression ratio of 17:1, ignition delay is shorter for all biodiesel blends than neat diesel due to higher cetane number
53	Jindal and Nandwana	2009	Jatropha oil methyl ester	TP & EC	Demonstrated that increase in compression ratio associated with increase in injection pressure improves the performance of the engine. Proposed that Smoke and CO emission reduce with use of biodiesel
54	Bajpai et al.	2009	Karanja oil and its blends with diesel	TP & EC	Pre heating of oil and blending with diesel was found to reduce the viscosity and with higher flash point, it was safe to store.
55	Banapurmath and Tewari	2009	Karanja oil and its methyl ester with producer gas	TP & EC	A gas carburetor was suitably designed to maximize the engine performance in dual fuel mode with Karanja oil–producer gas and Karanja oil Methyl Ester –producer gas respectively. Dual fuel mode of operation with carburetor resulted in better performance with reduced emissions.
56	Kandasamy and Thangavelu	2009	Rice bran oil and Pongamia oil	TP	Fuel tank with heater, temperature regulator and stirrer unit were the accessories used in the experimental set up for blending and heating the oil. It was observed that engine efficiency increases with increase in the temperature of biodiesel.
57	Baiju et al	2009	Methyl and ethyl esters of Karanja oil	TP & EC	Among the esters, ethyl esters emitted more NOx than methyl esters. This might be due to higher bulk modulus of ethyl ester than methyl ester.
58	Haldar et al	2009	Methyl ester of Putranjiva roxburghii oil	TP & EC	It was found that cetane number of Putranjiva oil is less than diesel which meant that ignition timing is crucial for better combustion and hence

					improves the engine performance and emissions.
59	Mani and Nagarajan	2009	Waste plastic oil	TP & EC	When compared to the standard injection timing of 23° BTDC, the retarded injection timing of 14° BTDC resulted in decreased oxides of nitrogen, carbon monoxide and unburned hydrocarbon while the brake thermal efficiency, carbon dioxide and smoke increased under all the test conditions.
60	Haldar et al.	2009	Oils of Putranjiva, Jatropha and Karanja	TP & EC	It was found that out of the three non edible oils tested, Jatropha yields best performance and emission at high loads
61	Bhale et al.	2009	Mahua oil methyl ester	TP & EC	It was noted that the fuel filter was clogged 30% more for biodiesel than that for diesel after 200 hours of operation. Blending Mahua methyl ester with ethanol and kerosene has improved the cold flow performance
62	Nagaprasad et al	2009	Castor oil and its blends with diesel	TP & EC	It was concluded that castor non-edible oil can be used as an alternate to diesel, which is of low cost. The investigators opined that usage of neat bio-diesel will have a great impact in reducing the dependency of India on oil imports.
63	Karabectas	2009	Rapeseed oil methyl ester	TP & EC	NO_x emissions were higher with biodiesel than that with diesel, while CO emissions were less with biodiesels. The higher oxygen content in biodiesels was stated as the reason for higher NO_x emissions
64	Qi et al.	2010	Soybean oil methyl ester	TP & EC	A minor increase in BSFC and decrease in BTE for biodiesel and its blends were observed compared with diesel fuel. The significant improvement in reduction of CO and smoke were found for biodiesel and its blends at high engine loads.
65	Panwar et al.	2010	Methyl ester of Castor seed oil	TP	It was concluded that the lower blends of biodiesel increased the break thermal efficiency and reduced the fuel consumption. The exhaust gas temperature increased with increasing biodiesel concentration indicating that Biodiesel is a viable alternative to diesel.
66	Aydin and Ilkilic	2010	Sunflower oil biodiesel	TP & EC	Blends of biodiesel and ethanol fuel can be used as alternative fuels in conventional diesel engines without any major changes. The NOx emissions were slightly increased with the use of both biodiesel–ethanol blend and standard diesel fuel with respect to those of the biodiesel–diesel blend
67	Sayin and Gumus	2011	Commercial biodiesel	TP	Finer breakup of fuel droplets obtained with increased IP provide

					more surface area and better mixing with air and this effect improved combustion.
68	Zhu et al.	2011	Commercial biodiesel blended with ethanol	TP & EC	The degree of reduction of NO_x and particulate matter reductions increased with increase in ethanol in the blends.

*TP- Thermal Performance, EC- Emission Characteristics, TP & EC – Thermal Performance and Emission Characteristics

Among the sixty-eight (68) studies reported in the Table 2.4, seven (7) studies are on thermal performance, fourteen (14) studies are on emission characteristics and remaining forty-seven (47) studies are on both thermal performance and emission characteristics.

There are various observations made by investigators in their respective studies. Some general observations which can be identified from the open literature are as follows:

- Biodiesels can be successfully used in existing diesel engines without any hardware modifications.
- The thermal efficiency of a biodiesel fuelled engine is observed to be slightly lesser than that of a diesel fuelled engine.
- The harmful exhaust emissions are generally lesser for all biodiesels as compared to pure diesel.

The different biodiesels which are considered by earlier investigators for studying the thermal performance and emission characteristics are Rapeseed, Polanga, Soybean, Palm, Jatropha, Sunflower, Cottonseed, Karanja, Putranjiva, Castor, Waste plastic oil, Ricebran, Mahua, Poon, Tall, Linseed, Canola, Sesame, Turpentine, Tobacco seed oil and Rubberseed oil. Most of the studies are conducted by blending biodiesels with pure diesel.

Very few studies appear to be reported in the open literature using Karanja biodiesel and Karanja oil as a fuel on diesel engine (Refer Table 2.5). Among 9 studies reported, 6 are conducted using Karanja biodiesel as fuel and the remaining using Karanja oil. It is found that all of them are studies related to the effect of load, blend, speed, injection timing, brake power, etc on thermal performance and emission characteristics.

Table 2.5 Studies Reported with Karanja Biodiesel On Thermal Performance and Emissions at Constant Compression Ratio

Sr. No	Investigators	Year	Fuel		Type of study (*TP/ EC/ TP & EC)	Parameters Varied
			Biodiesel	Oil		
1	Raheman and Phadatare	2004	Karanja biodiesel		TP & EC	Load, Blend
2	Banapurmath et al.	2008	Biodiesels from Karanja, Jatropha and sesame oil		TP & EC	Brake power, Blend, Injection Timing
3	Sureshkumar et al.	2008	Karanja biodiesel and its blends with diesel	Karanja oil	TP & EC	Load, Blend
4	Banapurmath and Tewari	2008	Karanja biodiesel	Karanja oil	TP & EC	Brake power, Blend, Injection Timing
5	Banapurmath et al.	2008	Karanja biodiesel with producer gas	Karanja oil	TP & EC	Brake power, Blend, Injection Timing
6	Bajpai et al.	2009		Karanja oil and its blends with diesel	TP & EC	Blend, Load
7	Murugu Mohan Kumar Kandasamy, Mohanraj Thangavelu	2009		Rice bran and Karanja oil	TP	Load, Blend
8	Baiju et al.	2009	Methyl and ethyl esters of Karanja oil		TP & EC	Load, Blend
9	Haldar et al.	2009		Oils of Putranjiva, Jatropha and Karanja	TP & EC	Load, Blend, Injection timing

*TP- Thermal Performance, EC- Emission Characteristics, TP & EC – Thermal Performance and Emission Characteristics

It is also observed that all the studies are conducted on a constant compression ratio engine at constant preset injection pressure (close to standard CR of 17.5, IP of 210 bar). Among the studies using Karanja biodiesel as fuel, there is no study reported for the evaluation of thermal performance and emission characteristics under different preset compression ratios and varied injection pressures.

Table 2.6 refers to the various studies conducted at different preset compression ratios using biodiesels other than Karanja.

Table 2.6 Studies with Varying Compression Ratios For Different Biodiesels Other Than Karanja

Sr. No	Investigators	Year	Fuel	Engine Variables
1	Raheman and Ghadge	2008	Mahua biodiesel	Load, Injection timing, Compression ratio, blend
2	Jindal et al.	2009	Jatropha biodiesel	Load, compression ratio, injection pressure
3	Anand et al	2009	Cottonseed oil methyl	Brake Mean Effective Pressure, Compression

			ester	Ratio, Blend
4	Sayin and Gumus,	2011	Commercial Biodiesel	Compression ratio, injection timing and injection pressure

2.3.2 Combustion Analysis

In this section, the review of studies based on combustion analysis of biodiesel fuelled engines is dealt with. Generally, the parameters generally considered to analyse the combustion processes of biodiesels in a CI engine are heat release rate, cylinder pressure, ignition delay, combustion duration, rate of pressure rise.

Senthil Kumar et al. [16] experimented with various methods of using vegetable oil (Jatropha oil) and methanol such as blending, transesterification and dual fuel operation. A single cylinder direct injection diesel engine was used for this work and was tested at constant speed of 1500 rpm at varying power outputs. The ratio of methanol to Jatropha oil was maintained as 3:7 on the volume basis. Jatropha oil and its methyl ester showed longer ignition delays as compared to diesel. According to the investigators, this was due to lower cetane numbers of jatropha oil and its methyl esters. The ignition delay was 11^0 CA with Jatropha oil, 10^0 CA with methyl ester, 12^0 CA with blend and 13^0 CA BTDC with dual fuel operation. The increase in the ignition delay with blend and dual fuel operation was attributed to the cooling effect produced by vaporisation of methanol. The peak cylinder pressure and maximum rate of pressure rise are minimum for Jatropha oil due to its high viscosity which leads to poor atomisation. However, the peak pressure with ester and blend were found to be higher due to the improvement in the preparation of air fuel mixture as a result of lower viscosity. Standard diesel showed highest peak pressure and rate of pressure rise. The duration of combustion was lowest for diesel and it increased in the ascending order for Jatropha methyl ester, blend, Jatropha oil, dual fuel operation. The highest combustion duration for dual fuel operation were attributed to the burning of inducted methanol by flame propagation

Banapurmath et al. [54] reported the results of research conducted in a four-stroke, single cylinder, water-cooled, direct injection, compression-ignition (CI) engine using Honge oil and blends of its ester. Experiments were conducted with injection timings of 19, 23 and 27^0 BTDC at various loads and at a constant rated speed of 1500 rev min^{-1}. The heat release rates, maximum rate of pressure rise, ignition delay, and combustion duration for Honge oil and Honge oil methyl ester (HOME) blended with diesel, to produce blends designated B20, B40 and B80, were determined. From the study, it was found that blends of HOME showed longer ignition delays when compared with diesel. However, the B20 blend exhibits a shorter ignition delay than the other blends. Peak pressure and maximum rate of pressure rise were highest for diesel followed by the B20 HOME blend. The peak pressures for B20, B40, B80 and B100 were measured at 78.50, 71.00, 69.25, 75.00 bar respectively compared with diesel which was 81.75 bar at full load. The combustion duration increased with an increase in the power output for all of the fuels. According to the investigators, the increase in power output was due to an increase in the quantity of fuel injected. Longer combustion duration was observed with HOME blends than for diesel due to the longer diffusion combustion phase.

Nadar and Reddy [63] modified a single cylinder, four stroke, diesel engine to work in dual fuel mode. To study the feasibility of using methyl ester of Mahua oil (MEMO) as pilot fuel, it was used as pilot fuel and liquefied petroleum gas was used as primary fuel. In dual fuel mode, pilot fuel quantity and injector opening pressure were varied as they affected the performance and emission of the engine. The values of injector opening

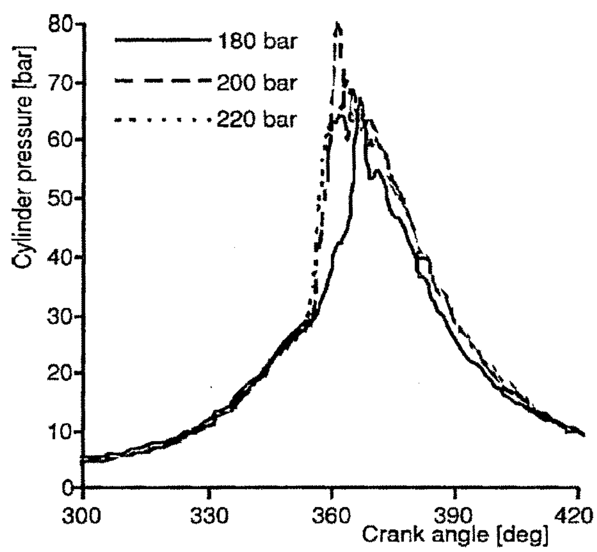

Figure 2.1 Pressure vs. Crank Angle at 3.88mg per cycle [63]

pressure selected were 180, 200 and 220 bar and pilot fuel quantity were 3.88, 5, 6.11 and 7.22 mg per cycle. The diesel engine was modified to work in the dual fuel mode by attaching an LPG line to the intake manifold. The pilot MEMO flow rate and LPG flow rate were varied by adjusting the fuel injection pump and the flow control valve, respectively. It was observed that the fuel injector opening pressure of 220 bar results in sudden pressure rise (Refer Figure 2.1). According to the investigators, the sudden rise in pressure was due to poor penetration of small quantity of pilot fuel, which results in accumulation of fuel nearer to the injector. The pilot fuel quantity of 5 mg per cycle resulted in a smooth pressure rise (Refer Figure 2.2).

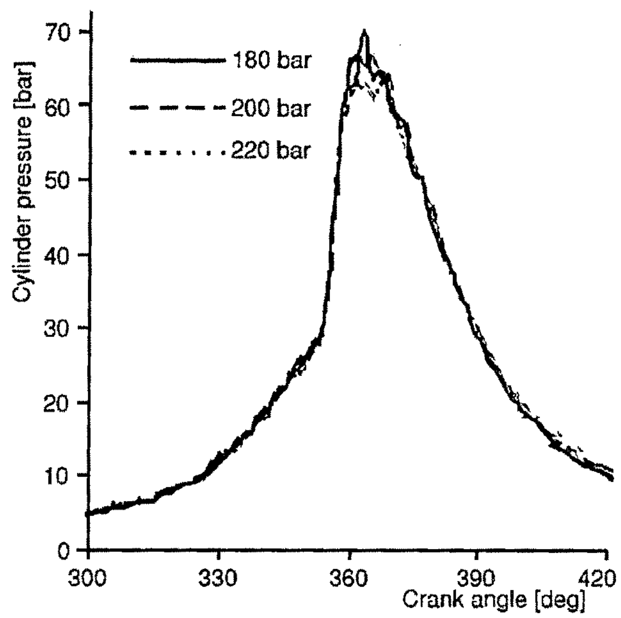

Figure 2.2 Pressure vs. Crank Angle at 5 mg per cycle [63]

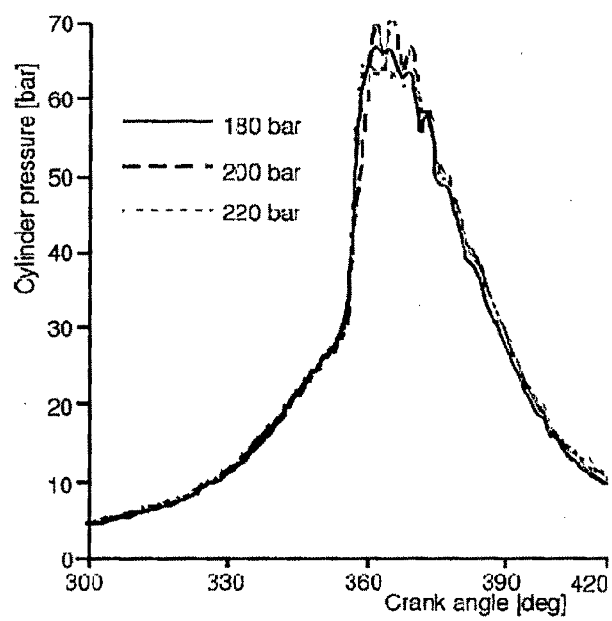

Figure 2.3 Pressure vs Crank Angle for 6.11 mg per cycle [63]

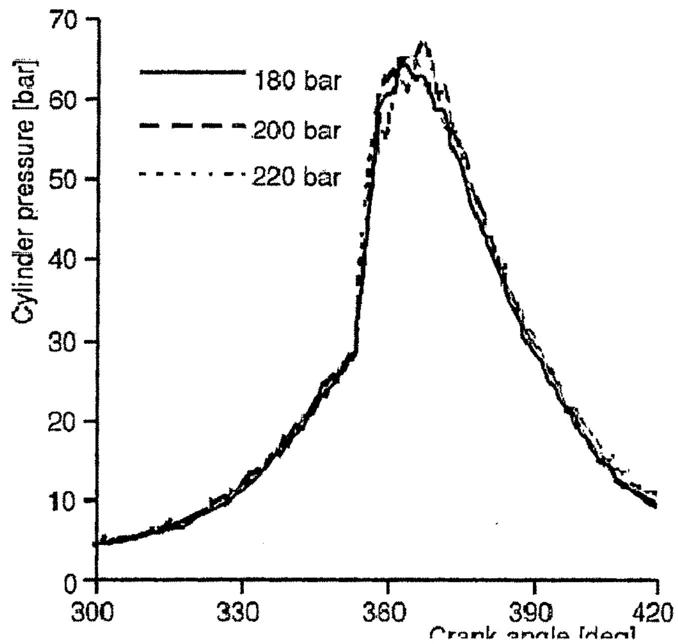

Figure 2.4 Pressure vs Crank Angle at 7.22 mg per cycle [63]

Devan and Mahalakshmi [64] analysed combustion of poon oil and poon oil based methyl ester (POME) in a single cylinder four stroke direct injection diesel engine. The blends were prepared with 20% Poon oil and 40% Poon oil methyl ester separately with standard diesel on volume basis. It was observed that the cylinder peak pressure for neat Poon oil and its blends with diesel was lower than that for standard diesel. This was attributed to more fuel-air mixture being burnt inside the cylinder before the peak pressure being achieved. However, the cylinder peak pressure at full load for Poon oil methyl ester and its diesel blend was higher than that of neat POME and its diesel blends. According to the investigators, this was due to the improvement in the preparation of air fuel mixture as a result of low fuel viscosity in case of POME – diesel blends. Standard diesel operation showed the highest peak pressure. Neat Poon oil did not show a pronounced heat release due to its higher viscosity which caused reduction in air entrainment and fuel/air mixing rates. For neat20 blend, the heat release was higher than that for neat Poon due to reduced viscosity and better spray formation. Thermal cracking of the double bond carbon chains during the injection process resulted in the breakdown unsaturated fatty acids of higher molecular weight compounds. These volatile compounds contributed to the better ignition quality of the vegetable oil despite the fact that vegetable oils had much higher viscosities than standard diesel.

Tashtoush et al. [82] conducted a study in which they used waste vegetable oil as a replacement to conventional diesel fuel in CI engines. They tested the performance and emission parameters of the engine by varying the air fuel ratio between10:1 to 20:1. About 100 litres of Waste Vegetable Oil (WVO) were collected from different local restaurants and brought into the labs of the Department of Applied Chemistry at Jordan University of Science and Technology (JUST) for treatment. The samples of WVO were decanted and then transesterified to produce the ethyl ester using acidic catalyst, HCl. All the esterified WVO samples used in this study were from used Palm oil since most local restaurants used palm oil.

In this study, it was observed that the combustion efficiency for both fuels (diesel and biodiesel) increased up to the stoichiometric A/F ratio (about 15) then started to decrease as the A/F ratio became leaner (Refer Figure 2.5). O_2 concentration in the case of biodiesel was higher at the two energy levels (Refer Figure 2.6). This is due to the addition of alcohol during the transesterification process in addition to the higher fuel oxygen present in biomass-based fuels including biodiesel. The general trend of the variation of O_2 with A/F ratio is in agreement with that of combustion efficiency as more O_2 is consumed with better combustion. The emission of CO is shown in figures which indicate that CO concentration declined with increasing A/F ratio for the two fuels at the two energy input levels.

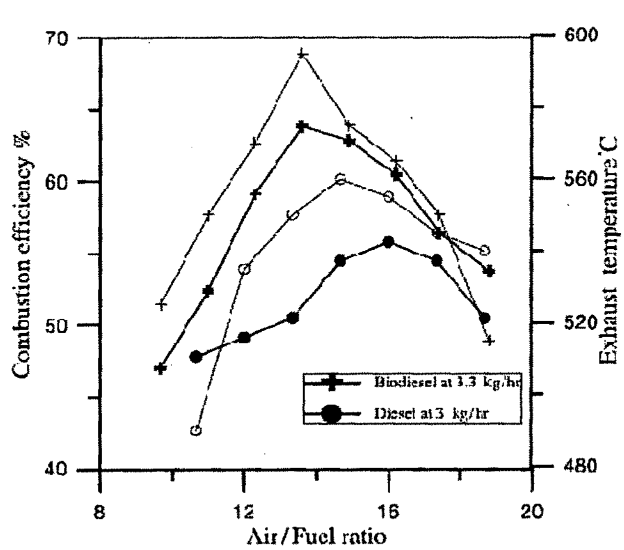

Figure 2.5 Variation of Combustion Efficiency and Exhaust Temperature with Air-Fuel Ratio [82]

It was also found that at the higher energy input, biodiesel combustion performance deteriorated and was inferior to diesel fuel due to its high viscosity, density and low volatility.

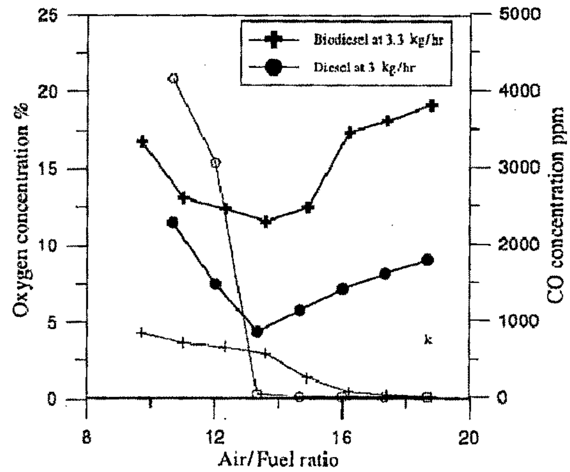

Figure 2.6 Variation of Oxygen Concentration and CO with Air-Fuel Ratio [82]

Tsolakis et al. [83] conducted the experiments on rape-seed oil on a diesel engine equipped with exhaust gas recirculation. The experiments were carried out on a Lister-Petter TR1 engine. The engine is a 773-cm^3, naturally aspirated, air cooled and single-cylinder direct injection diesel engine. The combustion of RME, B20 and B50 in the unmodified engine with pump–line–nozzle injection system resulted in advanced combustion compared to Ultra Low Sulphur Diesel (ULSD). The ignition delay was reduced while the initial uncontrolled premixed combustion phase (uncontrolled heat release phase) was increased. This resulted in increased cylinder pressure and temperature and hence early fuel ignition. The use of Exhaust Gas Recirculation (EGR) was more effective in the case of biodiesel blends combustion compared to ULSD combustion.

Canakci [84] tested biodiesel from soybean oil and compared the results with that of diesel in a turbocharged direct injection diesel engine. Commercially procured No. 1 and No. 2 diesel fuels tested as pure fuel (B100) and as 20% blend with No. 2 diesel fuel (B20). No. 2 diesel fuel had lesser cetane number than No. 1 diesel fuel. It was observed that for the B100, the start of combustion was earlier than for the No. 2 diesel fuel and this can be observed in the heat release rate profiles shown in Figure 2.7. B100 fuel was found to be start to burn at about 3.33^0 earlier than No. 2 diesel fuel while No. 1 diesel fuel was observed to start burning at about 0.25^0 later than No. 2 diesel fuel. It was found that the ignition delay for the B100 and No. 1 diesel fuel were shorter than for the No. 2 diesel fuel. B100 and No. 1 diesel fuel had about 1.06^0, 0.35^0 shorter ignition delay than No. 2 diesel fuel, respectively.

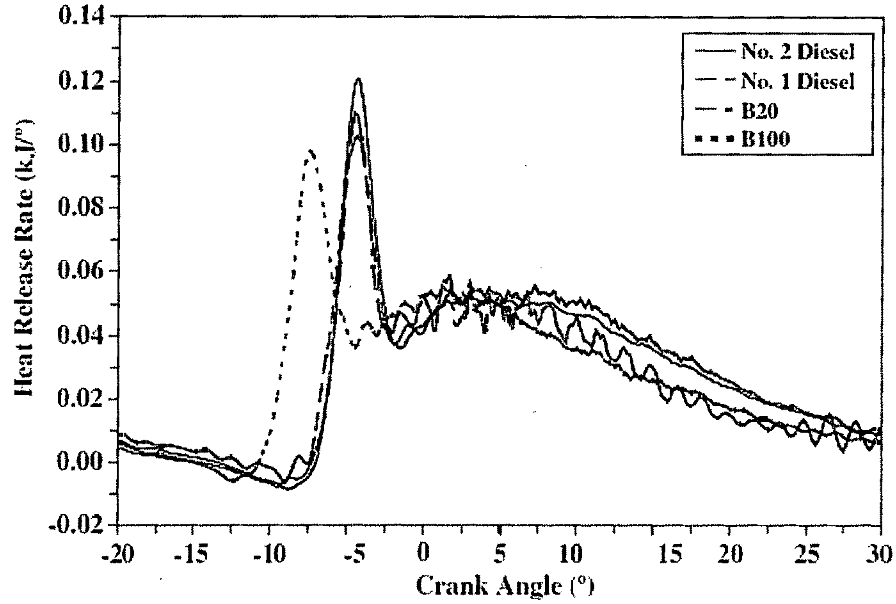

Figure 2.7 Comparison of Heat Release Rates for Different Fuels [84]

Gattamaneni et al. [85] used rice bran methyl ester(RBME) to conduct a study on combustion and emission performance on a 4.4 kW, constant speed, single cylinder, four-stroke, naturally aspirated, air-cooled, direct injection Kirloskar make diesel engine coupled to an electrical dynamometer for engine loading. They analyzed the performance and emission characteristics of Rice Bran Methyl Ester at variable loads whose properties were comparable to ASTM bio-diesel standards. It was observed that all the fuels exhibit a general trend of decrease in ignition delay with increase in load. According to the investigators, this was due to the rise in the cylinder gas temperature at the time of injection with increase in load. It was observed that at no load condition, the delay period for RBME decreased by 8% while its diesel blends showed almost 2% decrease for every 20% addition of RBME when compared to diesel. At 50 and 75% of the rated load, the delay period was decreased by 10 and 20%, respectively, for RBME compared to diesel. It was also observed that for every 20% addition of RBME in the RBME diesel blend the delay period decreased by almost 5% at all loads. This was attributed to the oxygen present in RBME and the breakdown of higher molecules of RBME to lower molecules of volatile compounds during injection and this advances the start of combustion resulting in decrease in ignition delay. The cylinder pressures for RBME and its diesel blends were found to be higher compared to diesel at all crank angles. This, according to the investigators, was due to earlier ignition of RBME and its diesel blends, which resulted in earlier start of combustion and hence higher pressure values compared to diesel. It was also observed that, the maximum rate of pressure rise decreased with increase of RBME in the fuel. This, according to the investigators, was a consequence of the decrease in ignition delay with increase in percentage of RBME in the fuel. They, further stated that reduced ignition delay implied, the quantity of accumulated fuel during ignition delay was lesser than during higher ignition delay. Hence, the pressure rise was not as drastic as in the case of diesel. Finally, they concluded that RBME and its diesel blends were suitable substitute for diesel as they showed satisfactory combustion and characteristics compared to diesel.

Sahoo and Das [86] undertook a study of combustion analysis of three different bio-diesels from non-edible oils namely Karanja, Jatropha and Polanga based bio-diesels for applications in generating sets and agricultural applications. Blends of B100, B20 and B50 were used at variable loads of 0%, 50% and 100% of full loads. The engine combustion parameters such as peak pressure, time of occurrence of peak pressure, heat release rate and ignition delay were computed. Combustion analysis revealed that neat Polanga bio-diesel that results in maximum peak cylinder pressure was the optimum fuel as far as the peak cylinder pressure was concerned. The ignition delays were consistently shorter for neat Jatropha bio-diesel, varying between 5.9° and 4.2° crank angles lower than diesel with the difference increasing with the load. Similarly, delays were shorter for neat Karanja and Polanga biodiesel when compared with diesel. Characterization of bio-diesels and effects of blends on cylinder pressure, heat release rate and ignition delay indicate that cylinder pressure is around 6.6 bar higher than HSD, delay is consistently shorter 4.2° to 5.9° crank angle and heat release is just closer to diesel and all bio-diesels considered above are quite suitable as fuels for diesel engine operations.

Buyukkaya [87] studied on the effect of biodiesel on the combustion characteristics of DI diesel engine. The biodiesel used for this purpose was the rapeseed oil methyl ester. It was found that ignition delay was shorter for neat rapeseed oil and its blends tested compared to that of standard diesel. The maximum heat release rates of standard diesel, B5, B20, B70 and B100 are 84, 79.7, 77.50, 74.9 and 72.2 J/ ^{0}CA, respectively. This was according to the author a consequence of the shorter ignition delay the premix combustion phase for neat rapeseed oil and its blends is less intense. The ignition delay slightly decreased with the use of biodiesels. According to the investigator, the chemical reactions during the injection of biodiesel at high temperature resulted in the breakdown of the high molecular weight esters. These complex chemical reactions led to the formation of gases of low molecular weight. Rapid gasification of this lighter oil in the fringe of the spray spreads out the jet, and thus volatile combustion compounds ignited earlier and reduced the delay period.

Table 2.7 compares the various studies conducted on combustion analysis using different biodiesels during the period from 2003 to 2010. The biodiesels include those made from Jatropha oil, Waste vegetable oil, Rapeseed oil, Soybean oil, Ricebran oil, Karanja oil, Mahua oil, Poon oil and Polanga oil. Most of the investigators have considered net heat release rate, cylinder pressure and ignition delay as parameters for analyzing the combustion characteristics.

Table 2.7 Summary of Studies On Combustion Analysis

Sr. No	Investigators	Year	Fuel	Combustion parameters studied	Remarks
1	Senthil Kumar et al.	2003	Jatropha oil blended with methanol	Peak cylinder pressure, Rate of pressure rise	Jatropha oil and its methyl ester showed longer ignition delays as compared to diesel. The peak pressure with ester and blend were found to be higher due to the improvement in the preparation of air fuel mixture as a result of lower viscosity.
2	Tashtoush et al.	2003	Waste vegetable oil	Combustion efficiency	It was observed that the combustion efficiency for both fuels (diesel and biodiesel) increased up to the stoichiometric A/F ratio (about 15) then started to decrease as the A/F ratio became leaner. It was also found that at the higher energy input, biodiesel combustion performance deteriorated and was inferior to diesel fuel due to its high viscosity, density and low volatility.
3	Tsolakis et al.	2007	Rapeseed oil methyl ester	Cylinder pressure, net heat release	With the use of biodiesel the ignition delay was reduced while the initial uncontrolled premixed combustion phase (uncontrolled heat release phase) was increased. This resulted in increased cylinder pressure and temperature and hence early fuel ignition.
4	Canakci	2007	Soybean oil methyl ester	Injection line pressure, Heat release rate	Biodiesel fuel was found to be start to burn at about 3.33^0 earlier than diesel fuel. It was also found that the ignition delay for the biodiesel was shorter than for diesel fuel.
5	Gattamaneni et al.	2008	Rice bran oil methyl ester	Ignition delay, peak pressure,	The cylinder pressures for RBME and its diesel blends were found to be higher compared to diesel at all crank angles. This, according to the

				rate of pressure rise, heat release rate,	investigators, was due to earlier ignition of RBME and its diesel blends, which resulted in earlier start of combustion and hence higher pressure values compared to diesel.
6	Banapurmath et al	2008	Karanja oil and its blends with ester	Ignition delay, Rate of pressure rise, Combustion duration, Heat release rate	Blends of Karanja methyl ester showed longer ignition delays when compared with diesel. Peak pressure and maximum rate of pressure rise were highest for diesel followed by the B20 blend
7	Nadar and Reddy	2008	Mahua methyl ester	Cylinder pressure	It was observed that the fuel injector opening pressure of 220 bar results in sudden pressure rise. According to the investigators, the sudden rise in pressure was due to poor penetration of small quantity of Mahua methyl ester, which results in accumulation of fuel nearer to the injector.
8	Devan and Mahalakshmi	2009	Poon oil methyl ester	Cylinder pressure,	It was observed that the cylinder peak pressure for neat Poon oil and its blends with diesel was lower than that for standard diesel. This was attributed to more fuel-air mixture being burnt inside the cylinder before the peak pressure being achieved.
9	Sahoo and Das	2009	Karanja, Jatropha and Polanga based bio-diesels	Cylinder pressure, heat release rate, ignition delay	Combustion analysis revealed that neat Polanga bio-diesel that results in maximum peak cylinder pressure was the optimum fuel as far as the peak cylinder pressure was concerned.
10	Buyukkaya	2010	Rapeseed oil methyl ester	Cylinder pressure, heat release rate	It was found that ignition delay was shorter for neat rapeseed oil and its blends tested compared to that of standard diesel. This was according to the author a consequence of the shorter ignition delay the premix combustion phase for neat rapeseed oil and its blends is less intense.

Among the 10 studies reported, only 2 are using Karanja biodiesel as fuel. In these studies Ignition delay, Rate of pressure rise, Combustion duration, Heat release rate and Cylinder pressure at constant compression ratio are only discussed.

From the exhaustive review carried out it is observed that no study on thermal performance and emission characteristics for Karanja biodiesel at different preset compression ratios with selected injection pressures appears to be reported. Further, it can also be noted that, no studies on combustion analysis using Karanja biodiesel as fuel wherein combustion parameters such as mass fraction burnt, net heat release rate, cumulative heat release rate, pressure volume plot, mean gas temperature and injection pressure are reported.

All studies made before the year 2000 are reviewed by A.S.Ramadhas et al. [96]. Only 11 studies refer to the thermal performance, emission characteristics of biodiesels as fuels on diesel engines at constant compression ratio. It appears from the open literature that the bulk of studies are conducted on the use of biodiesels as fuels only after 2000. Hence the studies conducted after 2000 have been focussed at present. Review related studies reported in the open literature are given in Appendix II.

2.4 Computational Study

Various computational based studies are also reported in the literature concerned with performance evaluation and emissions using pure diesel, biodiesel and biodiesel-pure diesel blends. They are either optimizsation studies using various techniques to optimise the thermal performance and emission constituents or using Artificial Neural Network (ANN) for modeling using experimental data to interpolate the performance and emission predictions. The studies related to multi-objective optimization are reviewed in Section 2.4.1 and that related to neural network modeling using ANN are reviewed in Section 2.4.2.

2.4.1 Optimization

Many techniques are available for optimization. Multi-objective optimization has gained momentum since the beginning of 21st century in almost all engineering fields. A review of literature related to optimization using multi-objective optimization applied to the thermal performance and emission characteristics of internal combustion engines show that there are only a few studies reported in general and diesel engines in particular. The studies are as follows:

Kesgin [88] developed a computer program which calculated the NO_x emissions with the input of engine speed and fuel data as well as the following data: zero dimensionally determined pressure, temperature, equivalence ratio, volume and mass depending on time in the burned zone, which are calculated by a two zone engine cycle simulation program. The validity of this program was verified by measurements from a turbocharged, lean-burn, natural gas engine. Using the results from this program, the effects of operational and design parameters of the engine were investigated. Then a wide range of engine parameters were optimised using a simple Genetic Algorithm regarding both efficiency and NO_x emissions. The results show an increase in efficiency as well as the amount of NO_x emissions being kept under the constraint value of 250

mg/Nm^3 in O_2 of 5%, which is the limit value for stationary internal combustion engines used in combined heat and power plants.

Shi [89] investigated optimal injection strategies for a heavy duty CI engine fuelled with diesel and gasoline like fuels. A CFD (Computational Fluid Dynamics) tool with detailed fuel chemistry was used to evaluate engine performance and pollutant emissions. The CFD tools feature a recently developed efficient chemistry solver that allowed the optimization tasks to be completed in practical computer times. A non-dominated sorting genetic algorithm II (NSGA II) was coupled with the CFD tool to seek optimal combinations of injection system variables to achieve clean and efficient combustion. This optimization study identified several key factors that play an important role in engine performance. It was found that the fuel volatility and reactivity play an important role in mid load condition, while at high load condition the performance of the engine is less sensitive to fuel reactivity. The study indicated that high volatility fuels such as gasoline and E10 are beneficial at high load giving good fuel economy.

Maheshwari et al. [90] reported the results of an experimental investigation of the performance of an IC engine fuelled with a Karanja biodiesel blends, followed by multi-objective optimization with respect to engine emissions and fuel economy, in order to determine the optimum biodiesel blend and injection timings complying with Bharat Stage II emission norms. Nonlinear regression was used to regress the experimentally obtained data to predict the brake thermal efficiency, NO_x, HC and smoke emissions based on injection timing, blend ratio and power output. AXUM software was used to determine the coefficients of the proposed functional relationship. To acquire the data, experimental studies had been conducted on a single cylinder, constant speed (1500 rpm), direct injection diesel engine under variable load conditions and injection timings for neat diesel and various Karanja biodiesel blends (5%, 10%, 15%, 20%, 50% and 100%). Retarding the injection timing for neat Karanja biodiesel resulted in an improved efficiency and lower HC emissions. The functional relationship developed between the correlating variables using nonlinear regression was able to predict the performance and emission characteristics with a correlation coefficient (R) in the range of 0.95-0.99 and very low root mean square errors. The outputs obtained using these functions were used to evaluate the multi-objective function of optimization process in the 0-20% blend range. The overall optimum was found to be 13% biodiesel-diesel blend with an injection timing of 24^0 BTDC, when equal weightage is given to emissions and efficiency.

A summary of the studies carried out on multi-objective optimization is shown in Table 2.8. It can be observed that only three (3) studies with multi-objective optimization are reported out of which two studies are based on Genetic Algorithm.

Table 2.8 Summary of Studies Carried on Multi-objective Optimization

Sr. No	Investigators	Year	Optimization technique used	Fuel	Remarks
1	Kesgin	2004	Genetic algorithm	Natural gas	Developed a computer program which calculated the NO_x emissions with the input of engine speed and fuel data
2	Shi	2010	Non-dominated sorting genetic algorithm II (NSGA II) was coupled with the CFD (Computational Fluid Dynamics) tool	Diesel and Gasoline	The CFD tools feature a recently developed efficient chemistry solver that allowed the optimization tasks to be completed in practical computer times. A Non-dominated sorting genetic algorithm II (NSGA II) was coupled with the CFD tool to seek optimal combinations of injection system variables to achieve clean and efficient combustion.
3	Maheshwari et al.	2011	Genetic algorithm	Karanja biodiesel and its blends with diesel	Nonlinear regression had been used to regress the experimentally obtained data to predict the brake thermal efficiency, NO_x, HC and smoke emissions based on injection timing, blend ratio and power output. AXUM software was used to determine the coefficients of the proposed functional relationship.

It can be observed from the table that only one (1) study **(Maheshwari et al. [105])** using Karanja biodiesel is conducted which involves optimizing the performance and emissions based on injection timing, blend ratio and power output.The engine used is at constant CR of 17.5 & IP of 205 bar.

2.4.2 Artificial Neural Network

ANN is used in predicting the output parameters of the engine with some input data available. It is a powerful modeling technique that investigators have employed in many engineering research studies. Few studies concerned with the application of ANN are reported predicting the thermal performance and emissions for conventional diesel engines. This section includes brief reviews of the studies related to ANN.

Najafi et al. [91] developed ANN based on their experimental work on an ethanol blended gasoline fuelled spark ignition engine. The results showed that the training algorithm of Back Propagation was sufficient for predicting engine torque, brake power, Brake Thermal Efficiency(BTE), volumetric efficiency, Specific Fuel Consumption(SFC)and exhaust gas components for different engine speeds and different fuel blend ratios. The ANN predictions for the brake power, engine torque, BTE, volumetric efficiency and BSFC yield a correlation coefficient (R) of 0.999, 0.995, 0.981, 0.985 and 0.986, respectively. It was found the root mean square error (RMSE) values were 0.74 kW, 0.49 N m, 0.59%, 0.48% and 0.003 kg/kWh for the brake power, engine torque, BTE, volumetric efficiency and BSFC, respectively. The ANN predictions for the brake power and torque yield a mean relative error (MRE) of 2.32% and 0.46% respectively. MRE of BTE was 1.28%. The ANN predictions for the volumetric efficiency yield an MRE of 0.48%. The ANN predictions for the BSFC yield MRE of 0.85%. The ANN predictions for the CO yield a correlation coefficient (R) of 0.994, RMSE of 0.18%V and MRE of 4.21%. Similarly R, RMSE, MRE for CO_2 emission were 0.985, 0.24%V and 1.54% respectively. The ANN predictions for the HC yield R of 0.987, RMSE of 5.41 ppm and MRE of 2.23%. The ANN predictions for the NO_x yield R of 0.973, RMSE of 89.85 pm and MRE of 5.57%. It was observed that the ANN model predicted engine performance and exhaust emissions with R in the range of 0.97−1. MRE values were in the range of 0.46−5.57%, while RMSE were found to be very low. There is a good correlation between the simulations from ANN and the measured data. Therefore, it was concluded that ANN is a useful method for simulating engine parameters.

Kiani et al. [92] modelled ANN to predict the engine brake power, output torque and exhaust emissions (CO, CO_2, NO_x and HC) of the engine. To acquire data for training and testing of the proposed ANN, a four-cylinder, four-stroke spark ignition engine was fuelled with ethanol-gasoline blended fuels with various percentages of ethanol (0, 5, 10,15 and 20%), and operated at different engine speeds and loads. An ANN model based on standard back propagation algorithm was developed using some of the experimental data for training. The back propagation neural networks (BPNN) were trained using the training sets formed by including 80 percent of data. After training, the BPNNs were tested using the testing datasets including 40 samples. There were three input and six output parameters in the experimental tests. The input variables are engine speed in rpm and the percentage of ethanol blending with the conventional gasoline fuel and engine load as percentage. The six outputs for evaluating engine performance include engine torque and brake power and emission parameters (CO, CO_2, HC, NO_x). The performance of the network can be evaluated by comparing the error obtained from converged neural network runs and the measured data. Error was calculated at the end of training and testing processes based on the differences between targeted and calculated outputs. The correlation coefficient between output and targets were all close to 1 which indicated that the performance can be predicted using this network. It was also observed that the ANN provided the best accuracy in modeling the emission indices with correlation coefficient of 0.98, 0.96, 0.90 and 0.71 for CO, CO_2, HC and NO_x, respectively.

Yusaf [93] used ANN modeling to predict brake power, torque, BSFC, and exhaust emissions of a diesel engine modified to operate with a combination of both compressed natural gas (CNG) and diesel fuels. The structure of ANN model used was as shown in the Fig. 2.8. Approximately 70% of the total experimental data (220 values) was selected at random and was used for training purpose, while the 30% was reserved for testing. The experimental data set for every output parameter includes 20 values, of which 14 values were used for training the network and six values were selected randomly to test the performance of the trained network. Simulations were performed using MATLAB. A multi-layer perception network (MLP) was used for non-linear mapping between the input and the output variable. To improve the modeling, several architectures were evaluated and trained using the experimental data. The back-propagation algorithm was utilized in training of all ANN models. This algorithm uses the supervised training technique where the network weights and biases are initialized randomly at the beginning of the training phase. The error minimization process is achieved using gradient descent rule.

The ANN predictions for the brake power, engine torque, brake thermal efficiency, brake specific fuel consumption and exhaust temperature yield a correlation coefficient (R) of 0.9808, 0.9884, 0.92897, 0.9838, and 0.9934 respectively.

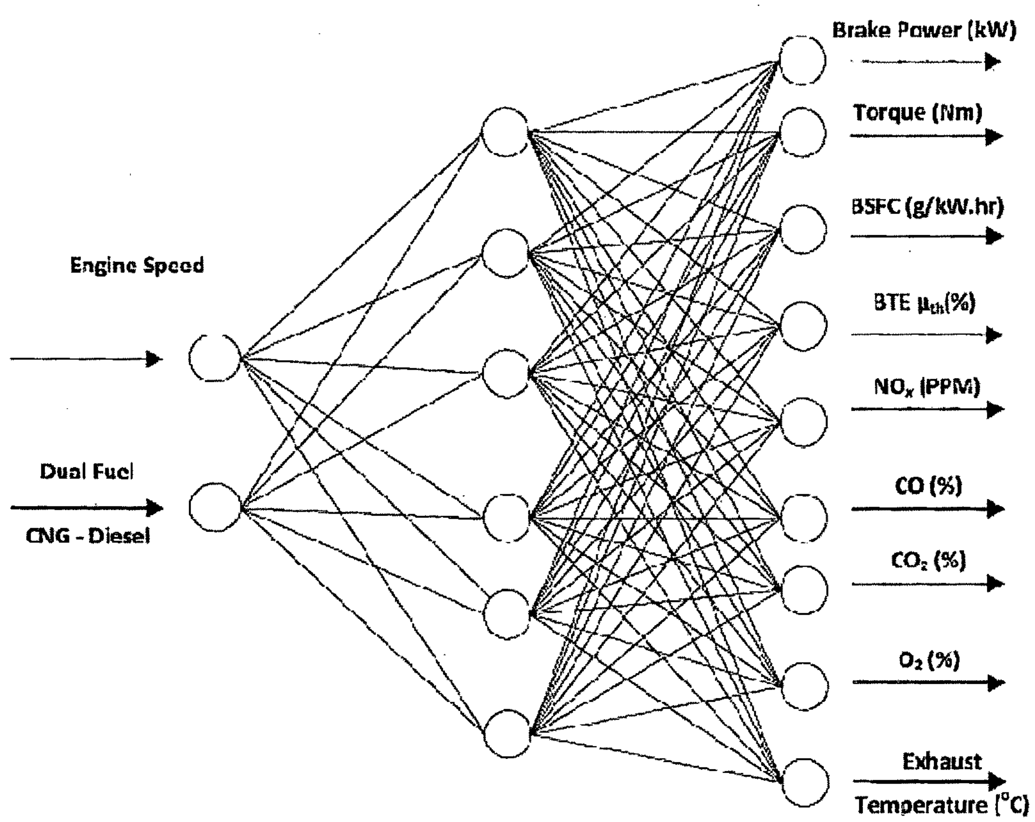

Figure 2.8 Structure of ANN for Dual Fuel (CNG-Diesel) Operated Diesel Engine [93]

Shivakumar et al. [94] used ANN was used to predict the engine performance and emission characteristics of an engine. Separate models were developed for performance parameters as well as emission characteristics. To train the network, compression ratio, injection timing, blend percentage, percentage load, were used as the input parameters where as engine performance parameters like BTE, BSEC, EGT ($T_{exh\ gas}$) were used as the output parameters for the performance model and engine exhaust emissions such as NO_x, smoke and (UBHC) values were used as the output parameters for the emission model. Out of 225 patterns, 70% (161 patterns) were used in the training set, 15% (32 patterns) in the validation set and remaining 15% (32 patterns) were employed for testing for both the models. For the performance and emission characteristics, the Mean Relative Error (MRE) was within 5% and 8% respectively which were found to be within the acceptable limits. For the combined model based on both the parameters, MRE was slightly more than the individual parameters and the accuracy of prediction slightly reduced. Hence, they suggested that individual models, rather than a combined model should be preferred. It was concluded that use of ANN reduces the experimental efforts and hence can serve as an effective tool for predicting the performance of the engine and emission characteristics under various operating conditions with different biodiesel blends.

Table 2.9 gives the summary of various studies conducted using ANN modeling.

Table 2.9 Summary Of Studies Carried Using ANN

Sr. No	Investigators	Year	Fuel	Engine type	(Fuel, engine type) Remarks
1	Najafi et al.	2009	Ethanol blended gasoline	Spark ignition engine with constant compression ratio	Developed ANN based on their experimental work on an ethanol blended gasoline fuelled spark ignition engine. The results showed that the training algorithm of Back Propagation was sufficient for predicting performance and emission parameters for different engine speeds and different fuel blend ratios.
2	Kiani et al.	2010	Ethanol blended gasoline	Spark ignition engine at constant compression ratio	An ANN model based on standard back propagation algorithm was developed using some of the experimental data for training. It was also observed that the ANN provided the best accuracy in modeling the emission indices with correlation coefficient of 0.98, 0.96, 0.90 and 0.71 for CO, CO_2, HC and NO_x, respectively.
3	Yusaf	2010	Compressed Natural gas	Diesel Engine at constant compression ratio	The back-propagation algorithm was utilized in training of all ANN models. This algorithm uses the supervised training technique where the network weights and biases are initialized randomly at the beginning of the training phase. The error minimization process is achieved using gradient descent rule.
4	Shivakumar et al.	2011	Biodiesel from Waste cooking oil	Diesel engine at variable compression ratio	Separate models were developed for performance parameters as well as emission characteristics.

Only few investigators seem to have developed neural networks based on their data obtained during experimental work. It appears that the field of ANN has emerged as a field of research in recent years and hence very few studies of its application in compression ignition engines are reported. Among four (4) studies reported, only one (1) study is conducted on a variable compression ratio diesel engine using biodiesel made from waste cooking oil as fuel.

It can be observed that very few computational studies involving multi-objective optimization and ANN are reported. From the review of various optimization studies it is identified that no study using Karanja biodiesel is reported where optimization is done based on compression ratio, injection pressure, load and blend. Also, according to the review on studies of ANN, no modeling using ANN for Karanja biodiesel fuelled diesel engine operated at different preset compression ratios and at different injection pressures appears to have been reported so far.

2.5 Scope of Present Study

From a systematic and exhaustive review of the earlier studies the scope of the present study is identified as follows. A large number of experimental studies are reported as seen in Section 2.3.1 to study the thermal performance of biodiesels used in diesel engines operated at constant compression ratio and constant injection pressure. In these studies the effect of load, blend, speed, injection timing, brake power, etc on thermal performance and emission characteristics are studied. In Section 2.3.2, studies related to combustion analysis using different biodiesels where combustion parameters like Ignition delay, Rate of pressure rise, Combustion duration, Heat release rate, Cylinder pressure, Combustion efficiency, Injection line pressure are presented. The fields of multi-objective optimization and ANN modeling on IC engine performance have emerged as areas of research in recent times. It is found that very few studies are reported in these areas.

The studies conducted on thermal performance, emissions characteristics, combustion analysis, multi-objective optimization using Karanja biodiesel on a diesel engine are listed in Table 2.10.

Table 2.10 Various types of studies using Karanja biodiesel at constant compression ratio

Sr. No	Investigators	Year	Fuel	Nature of work	Parameters varied / combustion parameters studied / optimized parameters
1	Raheman & Phadatare	2004	Karanja biodiesel	Thermal performance and Emission Characteristics	Load, Blend
2	Banapurmath et al.	2008	Karanja, Jatropha	Thermal performance	Brake power, Blend,

			and sesame oil methyl esters	and Emission Characteristics	Injection Timing
3	Sureshkumar et al.	2008	Karanja biodiesel	Thermal performance and Emission Characteristics	Load, Blend
4	Banapurmath et al.	2008	Karanja oil and its biodiesel with producer gas	Thermal performance and Emission Characteristics	Brake power, Blend, Injection Timing
5	Banapurmath and Tewari	2008	Karanja oil, its biodiesel and its blends with diesel	Thermal performance and Emission Characteristics	Brake power, Blend, Injection Timing
6	Bajpai et al.	2009	Karanja oil and its blends with diesel	Thermal performance and Emissions Characteristics	Blend, Load
7	Murugu Mohan Kumar Kandasamy, Mohanraj Thangavelu	2009	Rice bran and Karanja oil	Thermal performance and Emission Characteristics	Load, Blend
8	Baiju et al.	2009	Methyl and ethyl esters of Karanja oil	Thermal performance and Emission Characteristics	Load, Blend
9	Haldar et al.	2009	Oils of Putranjiva, Jatropha and Karanja	Thermal performance and Emission Characteristics	Load, Blend, Injection timing
10	Banapurmath et al	2008	Karanja oil and its blends with ester	Combustion analysis	Ignition delay, Rate of pressure rise, Combustion duration, Heat release rate
11	Sahoo and Das	2009	Karanja, Jatropha and Polanga based bio-diesels	Combustion analysis	Cylinder pressure, heat release rate, ignition delay
12	Maheshwari et al.	2011	Karanja biodiesel and its blends with diesel	Multi Objective Optimization using Genetic Algorithm	Injection timing, blend, power output
13	---	---	---	ANN	---

The following observations can be made from Table 2.10,

- It is clear that no studies on thermal performance and emission characteristics at different preset compression ratios and at different injection pressures using Karanja biodiesel as fuel are reported, although many studies have been conducted at a constant compression ratio.
- There is no study reported with Karanja biodiesel as fuel where combustion parameters like mass fraction burnt, net heat release rate, cumulative heat release rate, pressure volume plot, mean gas temperature and injection pressure are considered.
- It can be observed that in multi-objective optimization using genetic algorithm, only one (1) study using Karanja biodiesel is conducted which involves the optimization of performance and emissions based on injection timing, blend ratio

and power output. There appears to be no study reported where optimization is done for compression ratio and injection pressure.

- No neural network is modelled for Karanja biodiesel fuelled variable compression ratio CI engine.

Hence, the objectives of the proposed study are as under:

1. To experimentally evaluate the thermal performance and the exhaust gas emission characteristics of a diesel engine fuelled with Karanja biodiesel and its blends with diesel at different preset compression ratios and at different injection pressures in addition to varying loads.
2. To analyze the combustion parameters namely mass fraction burnt, net heat release rate, cumulative heat release rate, pressure volume plot, mean gas temperature, injection pressure in addition to rate of pressure rise and cylinder pressure.
3. To carry out multi-objective optimization on thermal performance and engine exhaust emissions based on compression ratio, load, injection pressure, blend using genetic algorithm technique to find the optimum operating conditions.
4. To model an ANN for predicting the engine performance and exhaust emissions of the variable compression ratio diesel engine used for the experimentation.

A flowchart depicting the proposed experimental and computational study is given in Figure 2.9.

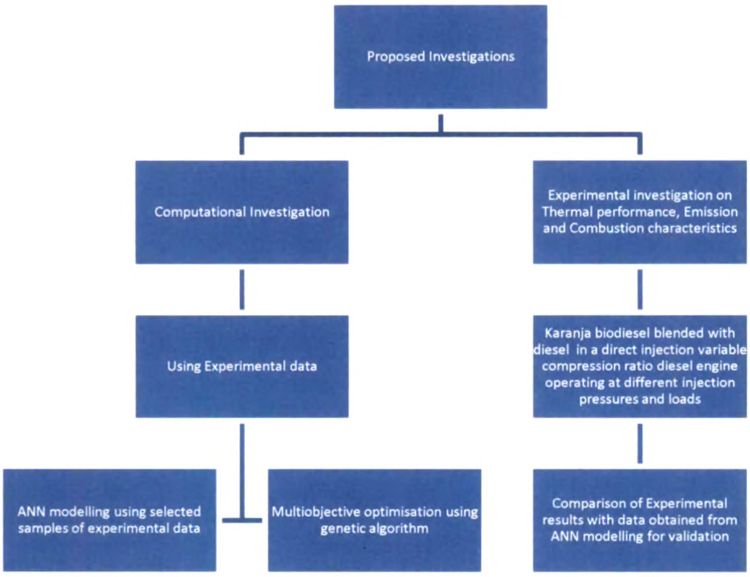

Figure 2.9 Flow chart for the proposed study

The proposed study consists of two parts.

1. Experimental study
2. Computational study

The experimental study is to be conducted on a four stroke, variable compression ratio diesel engine using Karanja biodiesel and its blends with diesel. The thermal performance and emissions characteristics are to be evaluated by running the engine at different preset compression ratios, different injection pressures and varying loads. The experimental study also consists of combustion analysis of the engine running on pure diesel and Karanja biodiesel at different preset compression ratios and full load.

The computational study consists of multi-objective optimization of thermal performance and emission characteristics and modeling an ANN for the engine. The multi-objective optimization is to be conducted by using genetic algorithm technique in order to get optimum performance and emissions of the engine when fuelled with blends of Karanja biodiesel and diesel. The ANN is modelled by using a set of selected results of the experimental study. The accuracy with which this neural network works will be judged by comparing the outputs from the network with the experimental data.